(NASA-CR-135501) STUDY OF CLUSTER STRUCTURE AND THRUST VECTOR CONTROL AND STUDY OF LARGE LAUNCH VEHICLES USING SOLID PROPELLANTS (PHASE 2, TASKS 1 AND 2) (Boeing Co., Seattle, Wash.) 176 p 00/99 N73-74194 Unclas 19503

CODE MLV
NASA HQ

CLASSIFICATION CHANGE
TO UNCLASSIFIED
By authority of E.O. 11652
Changed by L. SHIRLEY Date 5-10-73

JOINT PROGRESS REVIEW

STUDY OF CLUSTER STRUCTURE AND THRUST VECTOR CONTROL

Contract AF 04(611)8186

AND

STUDY OF LARGE LAUNCH VEHICLES USING SOLID PROPELLANTS (PHASE II, TASKS 1 AND 2)

Contract NAS 8-2438

D2-22002 AUGUST 7, 1962

THE BOEING COMPANY
AERO-SPACE DIVISION

#14 N. Rafel N.A.SA. Hdq.

[redacted]

JOINT PROGRESS REPORT

ON

STUDY OF CLUSTER STRUCTURE AND THRUST VECTOR CONTROL

Contract AF 04(611)8186

AND

STUDY OF LARGE LAUNCH VEHICLES USING SOLID PROPELLANTS

(PHASE II, TASKS 1 AND 2

Contract NAS 8-2438

D2- 22002

August 7, 1962

UNCLASSIFIED

The Boeing Company
Aero-Space Division
Seattle, Washington

Group 4
Downgraded at 3 year intervals;
Declassified after 14 years
DOD DIR 5200. 10

[redacted]

INTRODUCTION

This document is a compilation of data presented at the Joint Progress Review to representatives of the Air Force Flight Test Center and the George C. Marshall Space Flight Center, August 7, 1962, as required by the contract work statements of both contracts. With exception of Task No. 2 of Contract NAS8-2438, the work being accomplished under each contract is not separately identified in this document. The two work statements are complementary in nature and the study results are interdependent. Accordingly, the work can most clearly be presented as an integrated package. The NASA-MSFC Task No. 2 work is separately identified.

The AFFTC study objectives are to:

1) Establish the methods of design and evaluation of TVC systems and clustering structure for vehicles using solid propellant motors;
2) Demonstrate the application of these methods to integration of clustered motors and TVC systems in the preliminary design of two vehicles having specified mission capabilities.

The NASA-MSFC Task No. 1 study objectives are to perform preliminary design studies on a NOVA-class vehicle using solid-propellant motors in the first stage with emphasis on thrust vector control, vehicle staging, motor clustering, optimum motor design, facilities, logistics, development schedules, and funding. This vehicle is identical to one of the two vehicles considered for the AFFTC study.

The NASA-MSFC Task No. 2 studies are to provide basic design data on solid-boosted vehicles in the orbital payload range beyond 500,000 pounds and the solid-motor sizes required for such payloads.

Work on many of the items discussed herein is incomplete and the results given are preliminary. Trends are indicated, however, and tentative general conclusions can be drawn.

BASELINE VEHICLE SELECTION

VEHICLE CONSIDERATIONS

These studies are centered around two vehicles differing in mission profile and payload capacity as indicated. For brevity they are identified as 125K and 500K vehicles in data presented. The solid-motor first stages could consist of a broad range of cluster arrangements and motor diameters. The upper stages are constrained as noted. Three-stage-to-orbit and tandem-staged vehicles were not considered on the basis of previous studies which have been documented and distributed to the contracting agencies.

The overall studies have been approached by first establishing two baseline vehicles, each identifiable by the number and diameter of solid motors in the first stage, the number of engines in the upper stages (where applicable), and the approximate stage sizes. Using these baseline vehicles as reference, subsequent detail studies on cluster structure, TVC, motor optimization, staging, etc., are being performed. Upon completion of these detail studies (August 1962), the results will be incorporated and refined into baseline vehicles.

VEHICLE CONSIDERATIONS

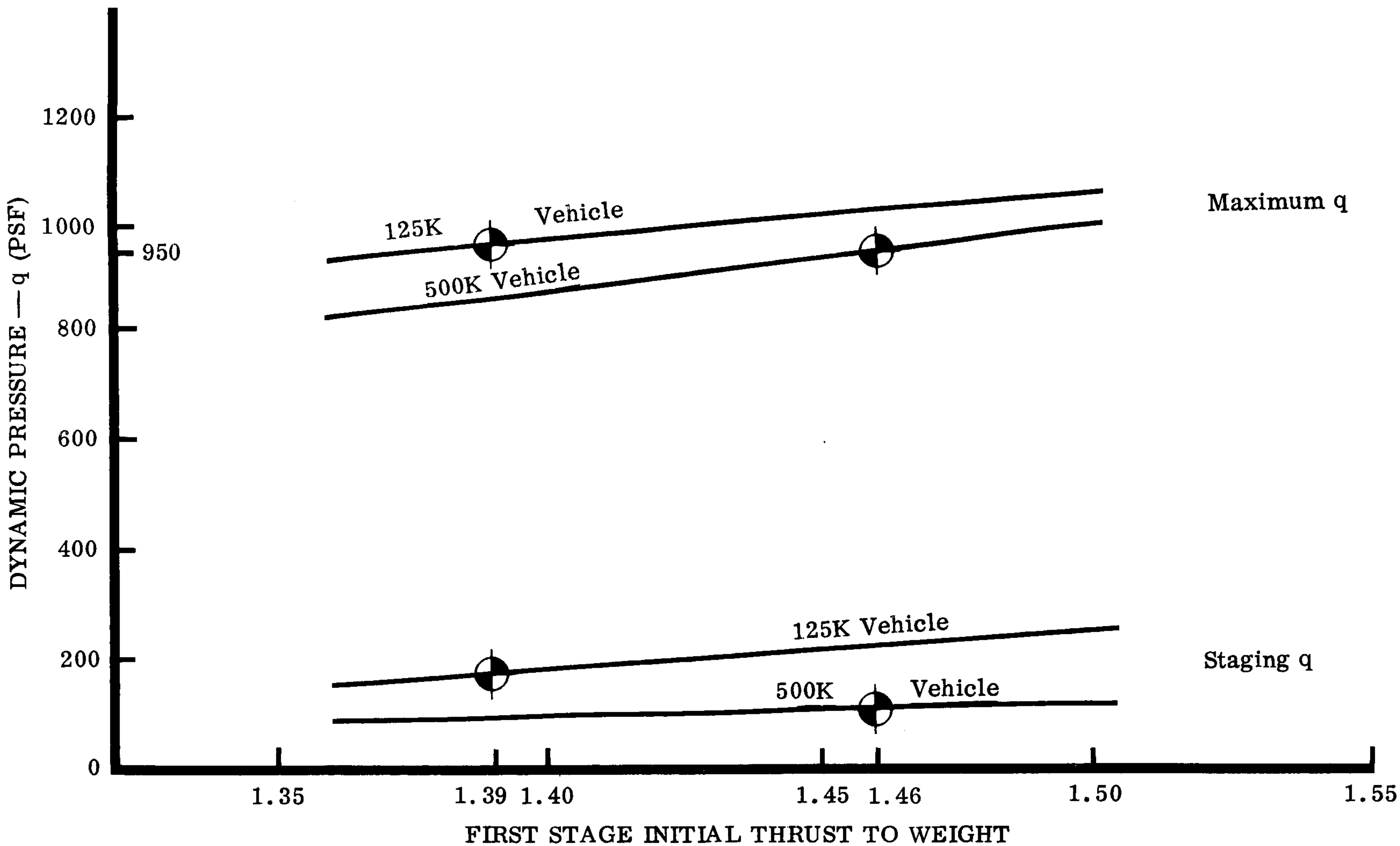
Vehicle	Mission	Stages			
		1		2	3
		Solid Motor			
		Dia	No.		
125K	125,000 lbs 300 n. mi. Orbit	120 in. to 280 in.	1 to 7	S-IIb	—
		Solid Motor			
		Dia	No.		
500K	500,000 lbs 177 km Orbit 170,000 lbs (Minimum) Escape	120 in. to 280 in.	4 to 14	M-1 Engines	J-2 Engines

SOLID-STAGE THRUST TO WEIGHT

The first-stage thrust-to-weight ratio upper limits are primarily limited by the maximum dynamic pressures allowable. With the upper limit being defined as 950 psi, the initial thrust-to-weight ratio for the 125K was set at 1.39 and at 1.46 for the 500K vehicle. Due to mission differences between the two vehicles, the 500K vehicle has a higher trajectory than the 125K and, as a result, the thrust-to-weight ratio can be higher.

SOLID STAGE THRUST TO WEIGHT

Neutral Burning Grains



PAYLOAD VERSUS LAUNCH WEIGHT

125K Vehicle

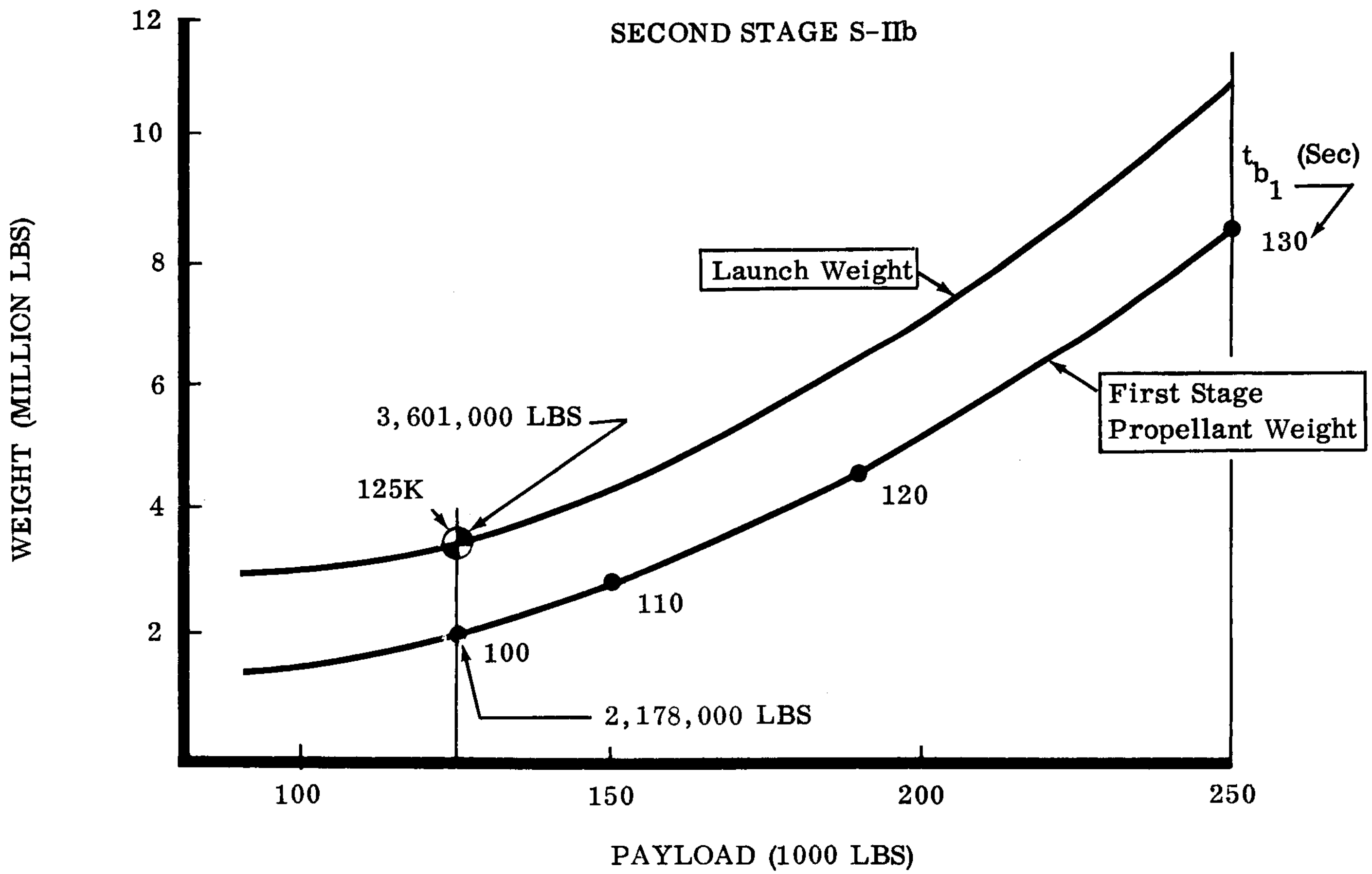
By definition, this vehicle uses the Saturn S-IIb second stage. Solid-propellant first-stage sizing was based on the S-IIb stage propellant loading of 930,000 pounds and with all five engines operating.

With a payload of 125,000 pounds delivered to a 300-nautical-mile orbit, the first-stage propellant weight, first-stage burn time, and total vehicle weight is approximated as shown. This vehicle, if staged to provide maximum payload-to-launch weight with the fixed second stage, would deliver an orbital payload of approximately 100,000 pounds. The magnification of first-stage and total vehicle weights as compared to payload increases may be noted. Although not shown, should a delivered payload of 250,000 pounds be required and the S-IIb used, a three-stage vehicle (first and second solid) would result in less total vehicle weight.

[redacted]

PAYLOAD VS LAUNCH WEIGHT

125K Vehicle



[redacted]

CONFIDENTIAL

STAGE SIZING

500K Vehicle

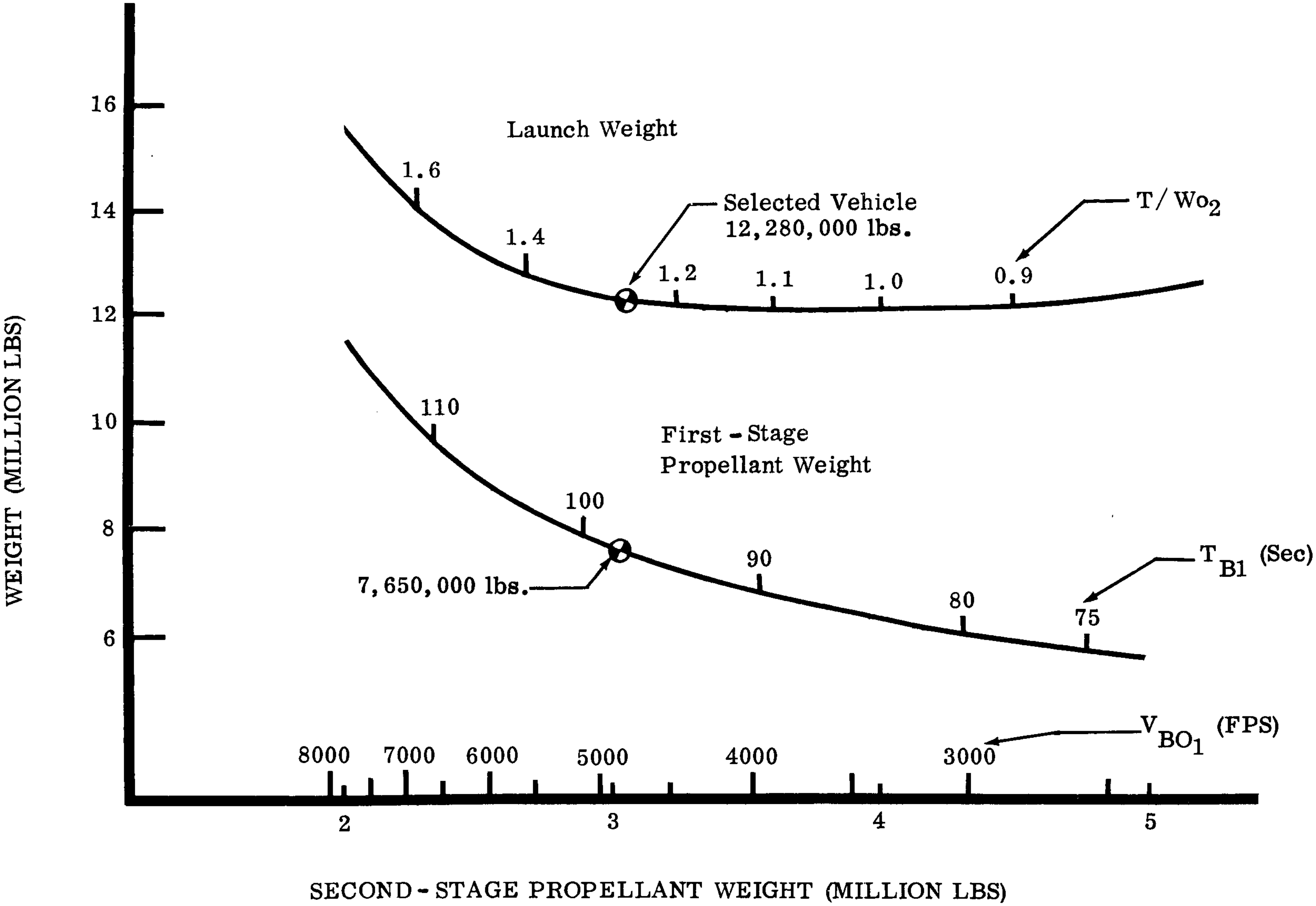
The 500K vehicle stage ratios were established on the basis of a mission profile that will escape its payload via delivery of a minimum of 500,000 pounds to a 177-kilometer parking orbit at the end of second-stage burnout. Neutral burning solid-propellant grain designs were assumed.

Vehicle performance optimization is based on the minimum launch weight for a 500,000-pound payload in the parking orbit. The plots show the variation of launch weight and first-stage solid-propellant weight with second-stage liquid propellant weight. These values vary considerably with changes in stage inerts. As a result, new values will be established for final vehicle design when the cluster structure and TVC system choices have been made.

CONFI [redacted]

STAGE SIZING

500K Vehicle



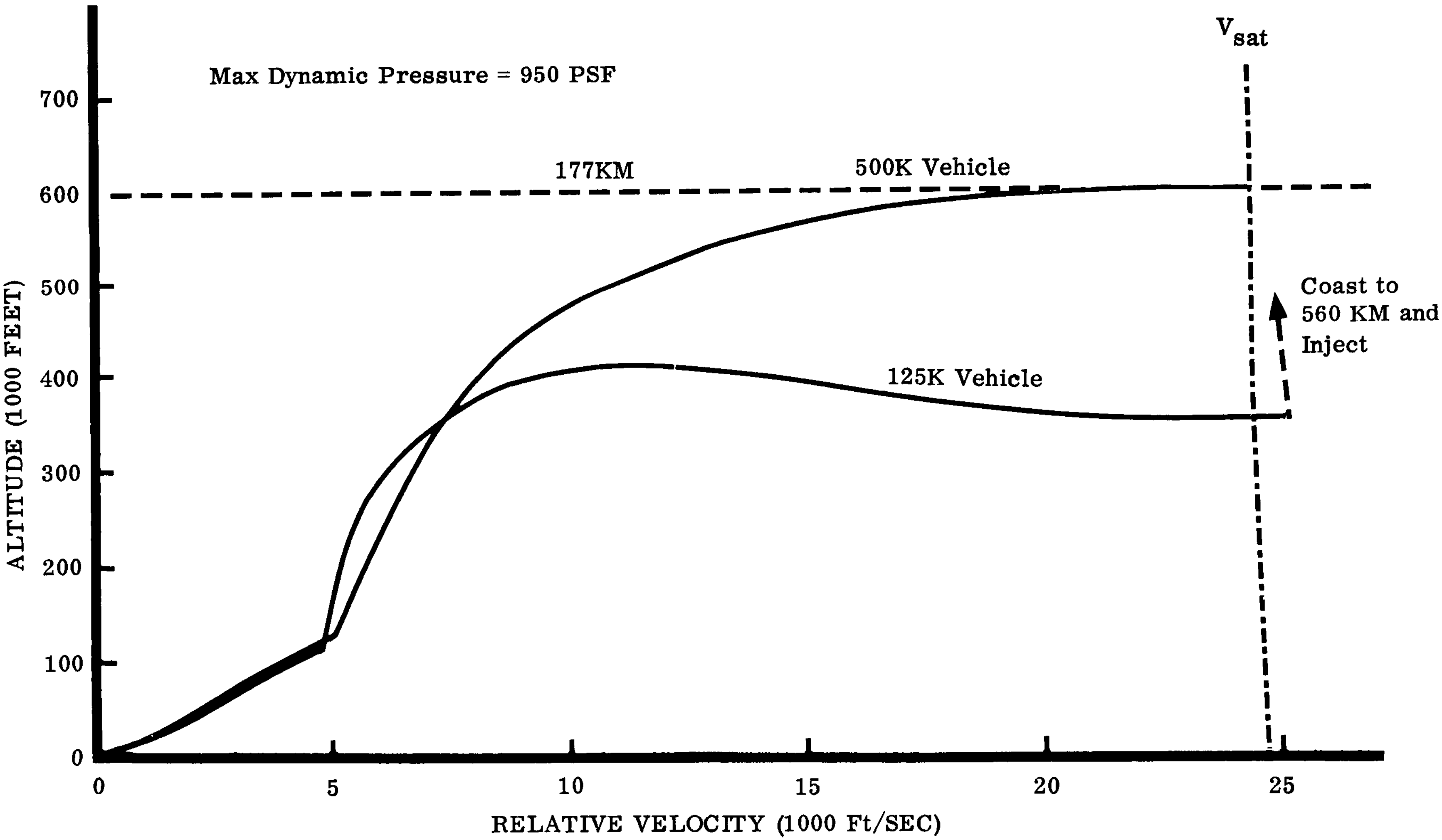
[redacted]

BASELINE TRAJECTORY CHARACTERISTICS

The two baseline vehicle trajectories are shown. The trajectory used consists of vertical lift-off to a velocity of 400 feet per second after which instantaneous tilt is initiated to follow a zero lift trajectory to burnout.

The 500K vehicle ascends directly to the 177 kilometer orbit, whereas the 125K vehicle ascends to 90 kilometers at supersatellite velocity and coasts to the 560 kilometer (300 n.mi.) orbit. Coast to orbit is the more efficient approach; however, for the lower 177 kilometer orbit, the penalty for direct ascent is not severe and the higher trajectory allows a higher launch thrust-to-weight ratio with the q_{max} limit.

BASELINE TRAJECTORY CHARACTERISTICS



SUMMARY OF INFLUENCES

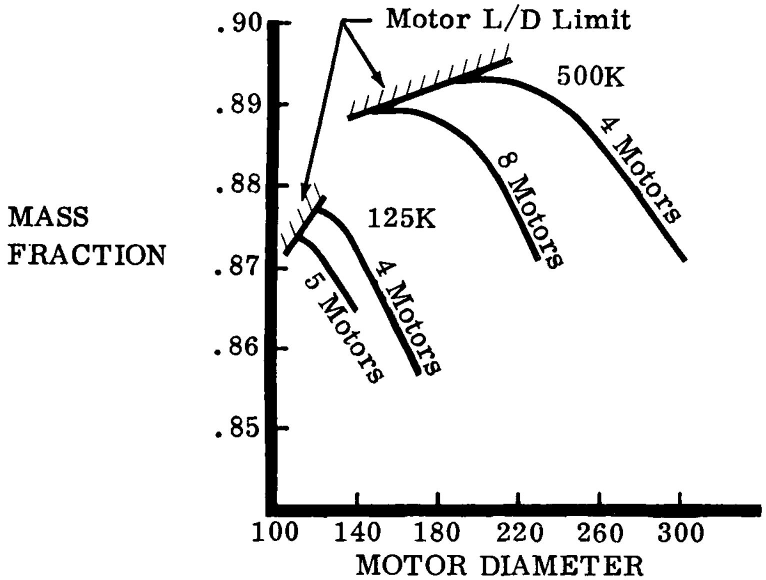
Mass fraction values are highest for a given payload and motor chamber pressure when (1) the least number of motors are used in a cluster, and (2) when the motor length to diameter is as high as practical.

In terms of reliability, a single motor should be used, but such an arrangement is not practical for the vehicles under study. Clusters of two or three have safety implications which tend to offset their otherwise favorable reliability. In the event of motor out, the thrust-to-weight ratio would be less than that for lift-off. Also, less chance exists to exercise control authority in event of TVC malfunction. The cluster of four is considered the next most practical if a single motor cannot be used.

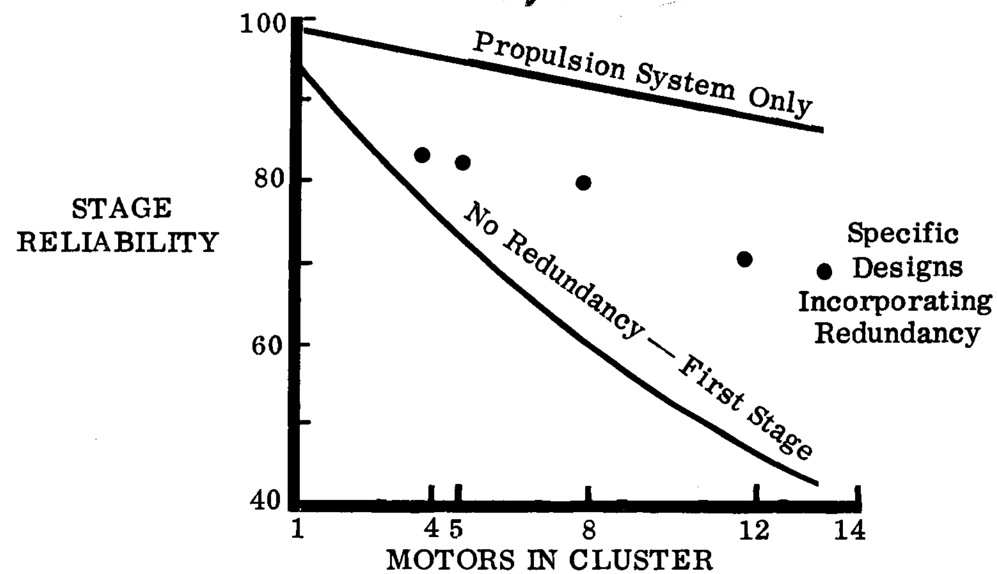
Total system costs tend to be lower as fewer motors are used in a cluster and as motor length to diameter is increased.

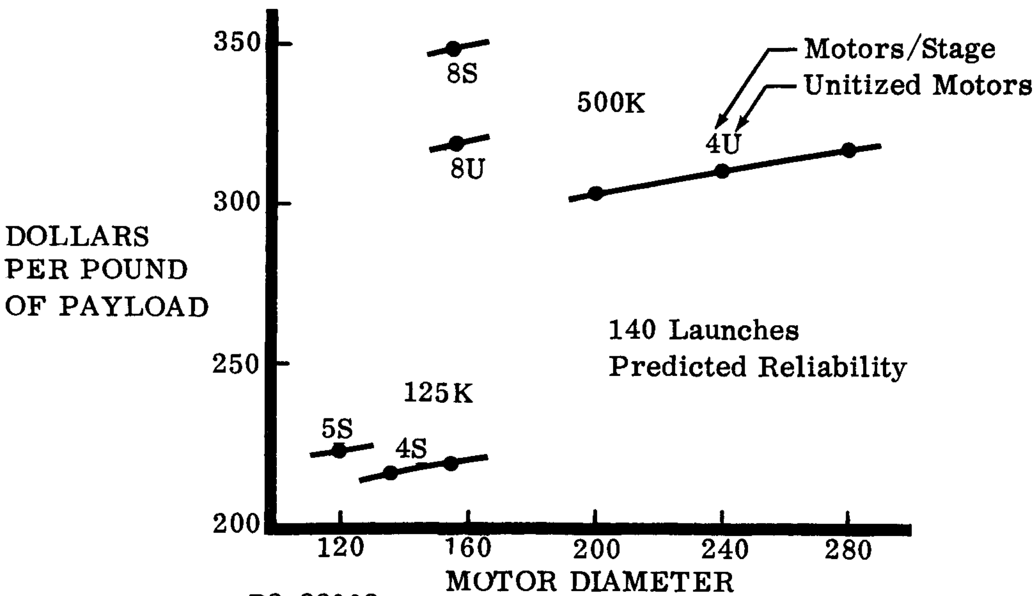
SUMMARY OF INFLUENCES

Mass Fraction – Costs – Reliability



based on 140 launches





CONCLUSIONS

4 Motor Cluster

- High Reliability
- High Mass Fraction
- Low Cost

MATRIX ANALYSIS

500K Vehicle

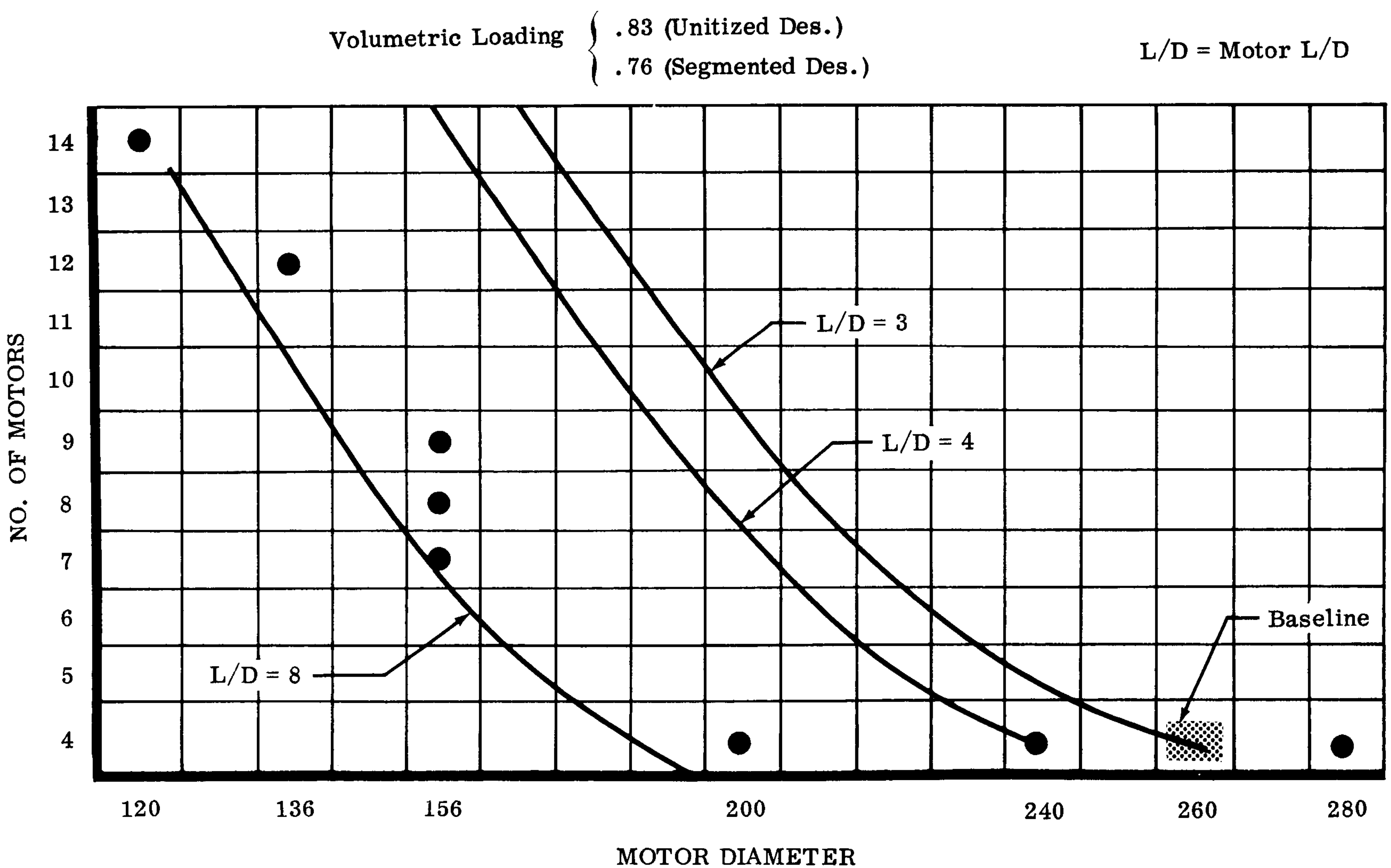
The matrix of possible cluster combinations for the 500K vehicle was first established as shown in the simple rectangular chart of numbers of motors versus motor diameters. Motor L/D limits were superimposed to establish practical limits for consideration. The "L/D - 3" limit was regarded not as a firm limit but as a good design limit. The "L/D = 8" limit is a much firmer limit representing a configuration having a segmented motor volumetric loading of .76 and representing a fully grown motor. The "L/D - 4" line is included to show the shift in the limit line if the volumetric loading capability (.83) of a unitized motor is used.

Configurations considered worthy of interest have been indicated. The concern for high reliability is reflected by the pattern of the indicators tending to follow the limit line until reaching a cluster of four motors. Clusters of fourteen 120-inch motors and seven 156-inch motors appear to be very marginal choices since no growth capability exists. The clusters of four indicate that the 200-inch motor will be longest and will have a small growth capability. 240- and 260-inch motors appear as good designs. The 280-inch motor appears larger than needed for the study vehicle.

The matrix indicates that the best motor diameter in a cluster of four, lies in the 200- to 260-inch-diameter group. Further analysis is being conducted to define more specifically optimum motor sizes.

[redacted]

MATRIX ANALYSIS
500K Vehicle



[redacted]

MATRIX ANALYSIS

125K Vehicle

The matrix for the 125K cluster possibilities was established as for the 500K vehicle. L/D limits were shown for segmented motor limits since all motors considered were for segmented design except the 200-inch diameter motor.

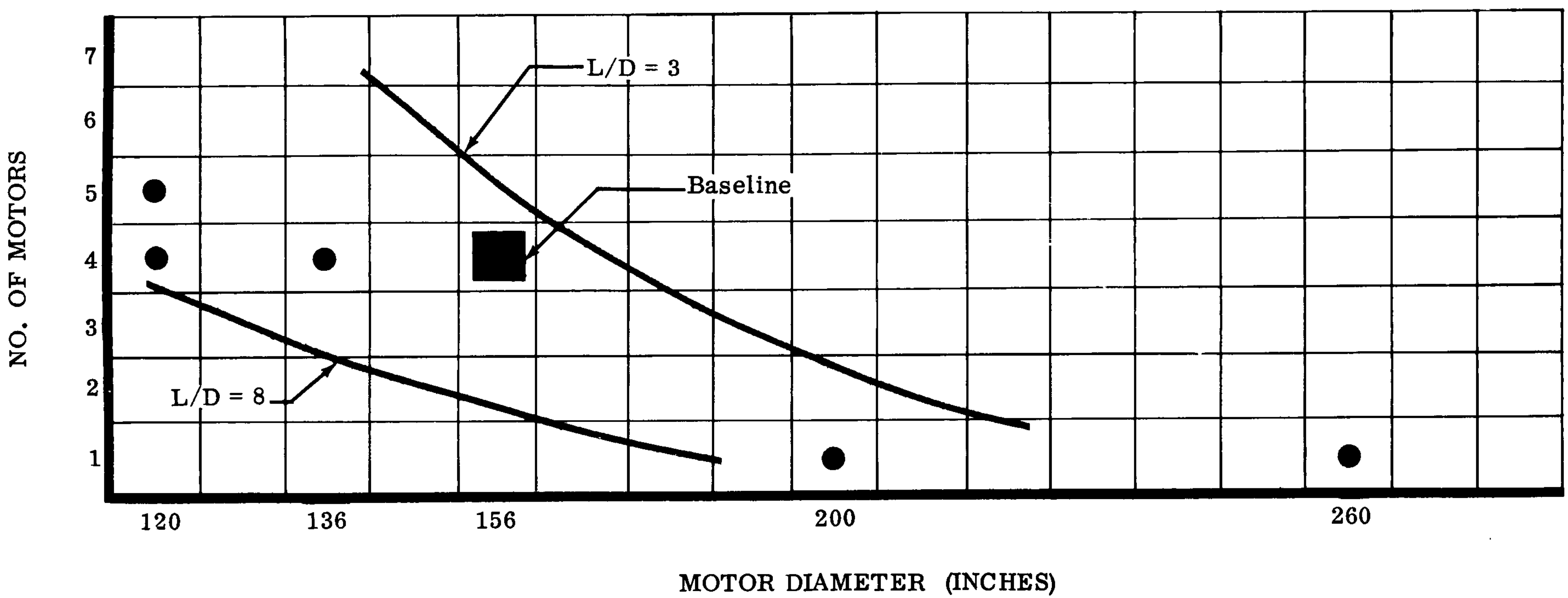
Clusters of two and three were not considered for reasons previously discussed. The single motor and the cluster of four 120-inch motors appear good on the matrix, but their small diameter, in combination with the 396 inch diameter of the S-IIb stage, presents an undesirable setback configuration at the interstage. The setback creates a unique structural problem, complicates nozzle clearances for the upper stage, and adds to vehicle instability and drag. The cluster of four 136-inch motors retains much of the above disadvantage but could be considered a candidate. The cluster of five 120-inch motors retains some setback problems but is the best competition to the cluster of four 156-inch motors. In consideration of growth possibilities, reliability, and cost, the cluster of four 156-inch motors was chosen for the baseline configuration.

MATRIX ANALYSIS

125K Vehicle

Volumetric Loading = .76 (Segmented Design)

L/D = Motor Length to Diameter



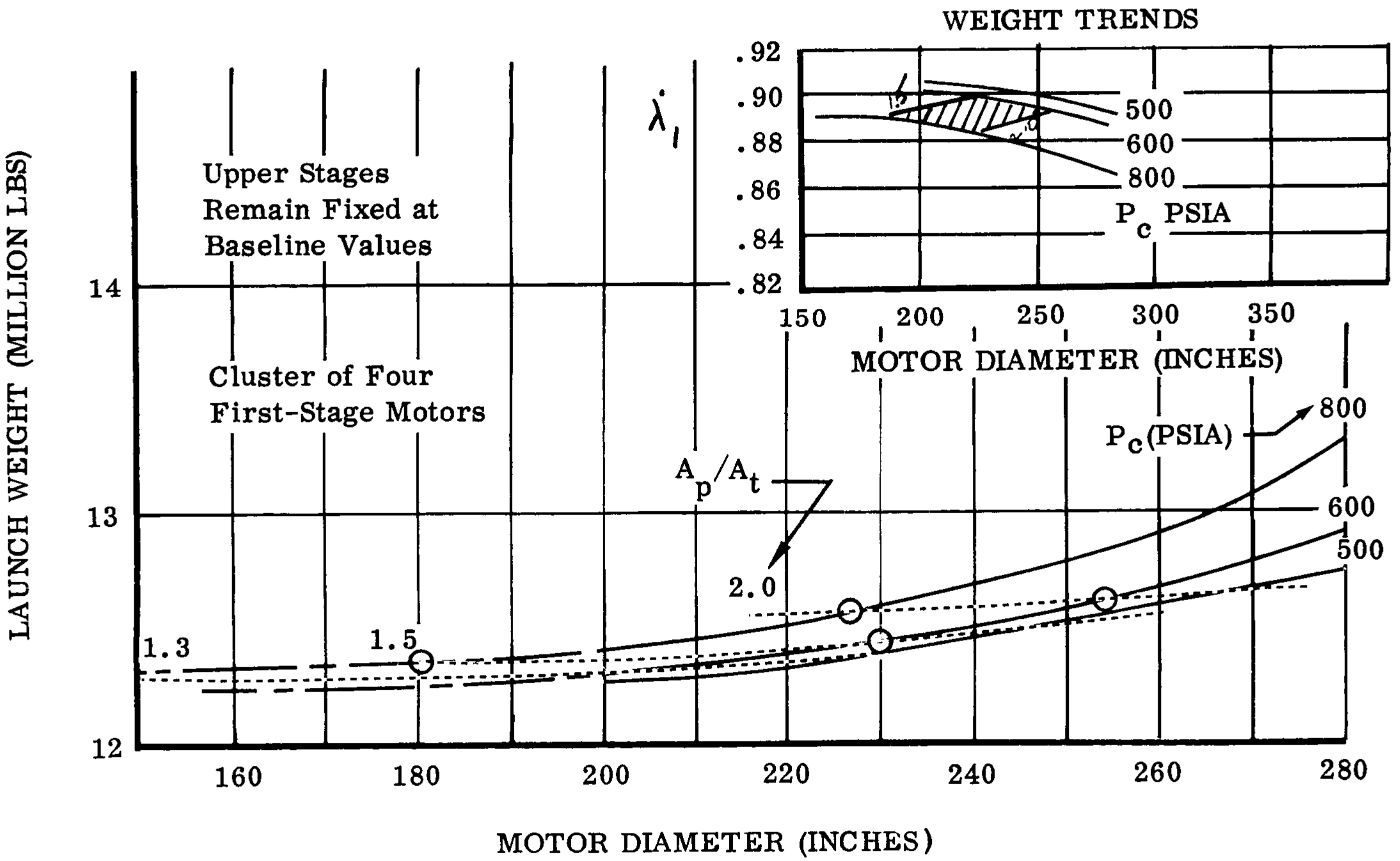
FIRST STAGE MOTOR DIAMETER

500K Vehicle

The preceding matrix, mass fraction, and cost analyses indicated trend effects for motor diameter selection. Preliminary analyses of performance were also conducted to reveal trades of launch weight, port-to-throat ratio, and mass fraction as shown. The best motor diameter appears to be in the 200- to 240-inch range. Contrary to cost and mass fraction trends, the larger size could be preferred in view of growth potential. Receipt of information that a 260-inch-diameter motor had the best probability of development, and knowledge that the larger size was not seriously off-optimum led to its adoption for the baseline 500K vehicle. Subsequent studies on motor optimization are reported in otner sections herein.

FIRST-STAGE MOTOR DIAMETER

500 K Vehicle



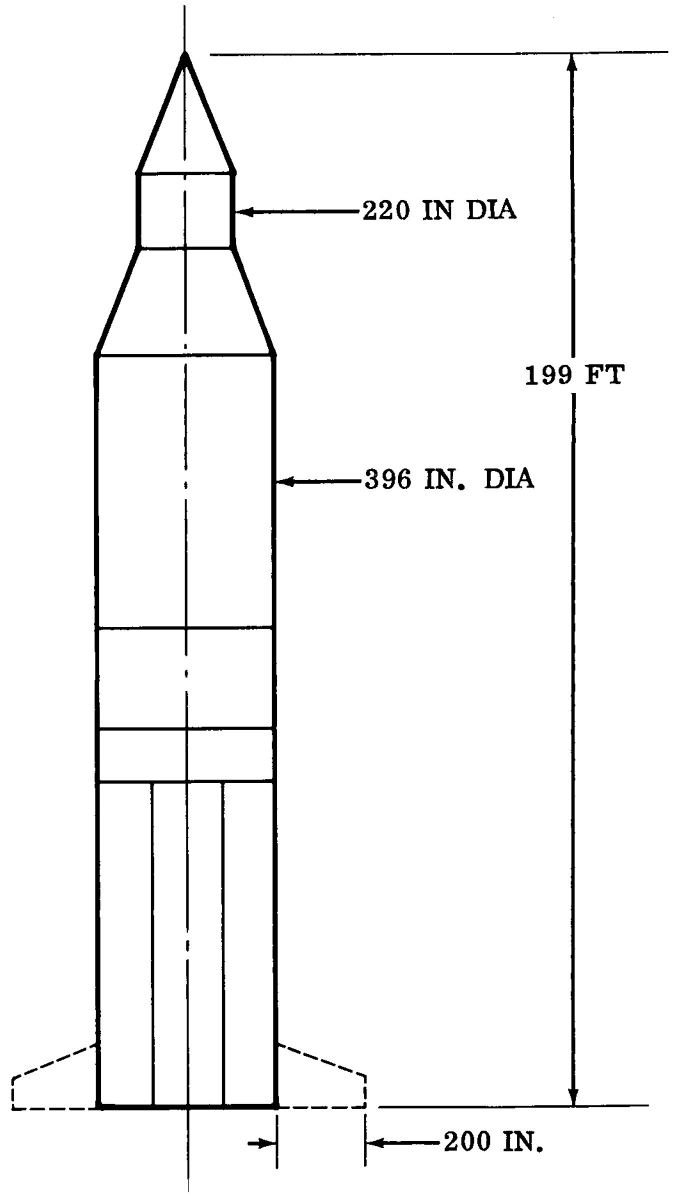
125K BASELINE VEHICLE

The 125K baseline vehicle is shown with a cluster of four 156-inch-diameter segmented solid motors constituting the first stage. Fins shown illustrate the size required for neutral stability. The finned and finless vehicles will be discussed in the thrust vector control portion of this report.

[redacted]

125K BASELINE VEHICLE

PAYLOAD	125,000 LBS
S-IIb STAGE	
5 J-2 ENGINES	
W_{P2} LO_2/LH_2	930,000 LBS
W_{O2}	1,132,000 LBS
4 156 IN. SOLID MOTORS (SEG.)	
W_{P1}	2,178,000 LBS
W_{O1}	3,601,000 LBS



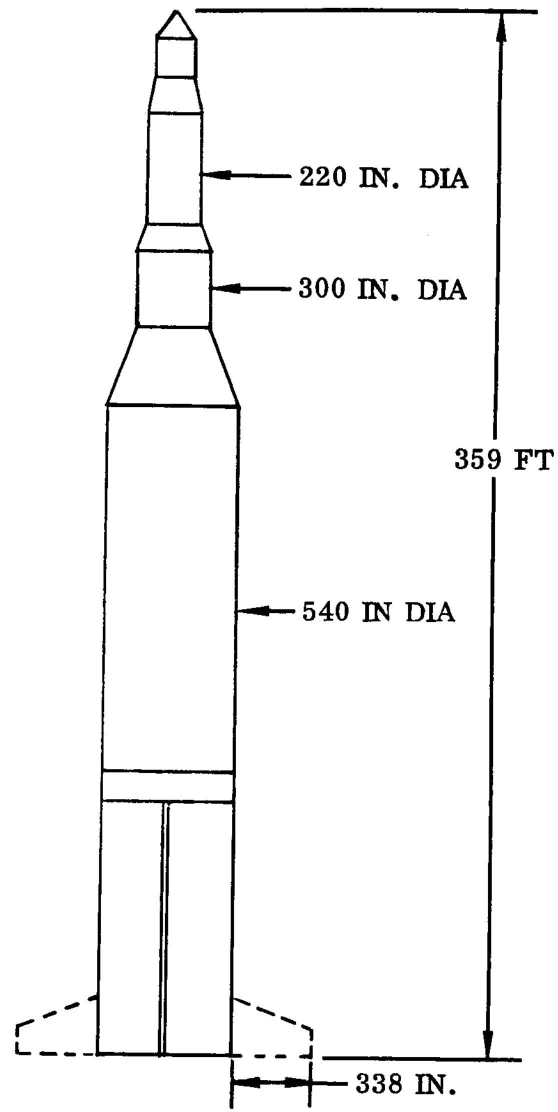
[redacted]

500K BASELINE VEHICLE

The 500K baseline vehicle is shown with a cluster of four 260-inch-diameter unitized solid motors constituting the first stage. The second and third stages are LO_2/LH_2 stages with four M-1 engines powering the second stage and one J-2 the third stage. Fins needed for neutral stability are shown. The finned and finless vehicles will be evaluated in the thrust vector control portion of this report. This vehicle and the preceding 125K vehicle are the two baselines for conducting the further portions of the study.

500K BASELINE VEHICLE

PAYLOAD		203,800 LBS
1	J-2 ENGINE	
W_{P3}	LO_2/LH_2	273,000 LBS
W_{O3}		500,000 LBS
4	M-1 ENGINES	
W_{P2}	LO_2/LH_2	3,000,000 LBS
W_{O2}		3,757,000 LBS
4	260 IN. SOLID MOTORS (UNITIZED)	
W_{P1}		7,650,000
W_{O1}		12,280,000



BLANK

DYNAMICS AND CONTROLS

A. L. Caldwell

DYNAMICS AND CONTROL ANALYSES

The parametric dynamics and control studies consist of control requirements analyses for two vehicle sizes, each with three stability levels. These parametric studies provide the basic control requirements for the TVC system hardware studies and allow the best matching between vehicle design and each TVC system required. The variations in vehicle size and stability will allow application of this data to similar vehicles other than the two specifically identified herein.

In addition to the parametric studies, launch and stage separation dynamics analyses are being performed for the 500K unfinned vehicle to define control and vehicle design requirements for those flight conditions.

DYNAMICS AND CONTROL ANALYSES

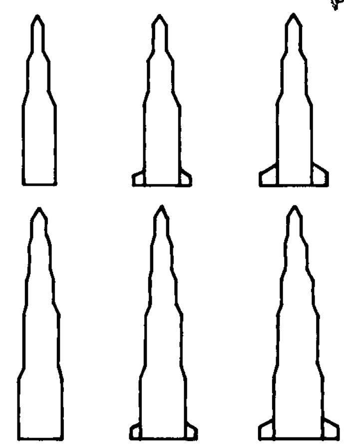
Neutral Stability at Max Q

PARAMETRIC ANALYSES

- Vehicle Aerodynamic Stability
- Closed-Loop Control Deflection and Impulse From Continuous Boost Simulation
- Dynamic Stability and Response From Point Analog Simulation

125K

500K



FLIGHT DYNAMICS ANALYSES

- Launch
- Stage Separation

500K

CONTROL TIME HISTORY — 500K VEHICLE

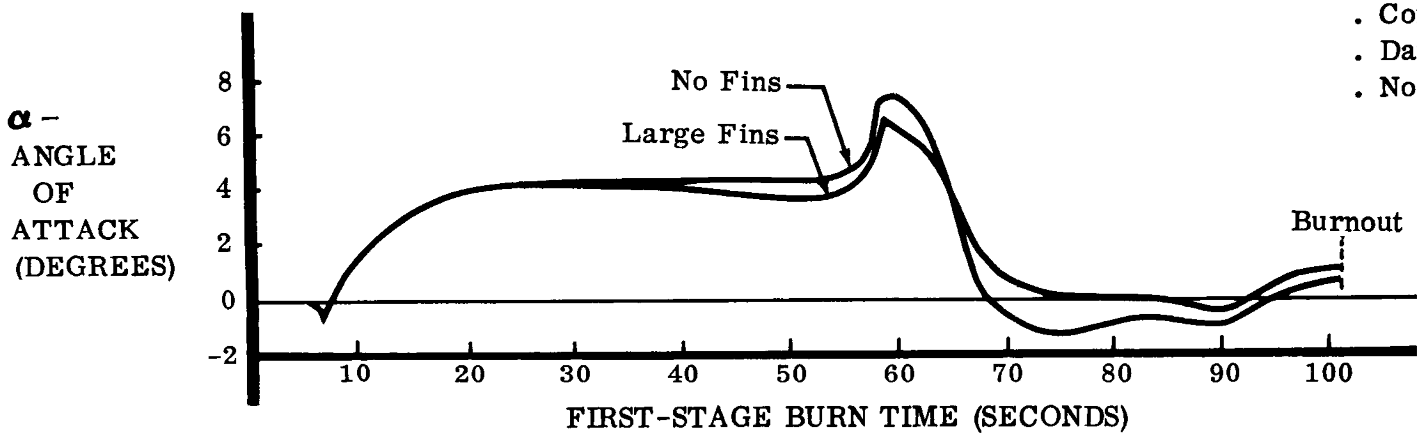
Thrust deflection angle and angle of attack are shown during first stage boost for the 500K payload vehicle as calculated by a continuous boost simulation. In this simulation, all thrust is deflected, no control mass is expended, and a perfect autopilot is assumed. These assumptions are most consistent with the moveable nozzle TVC system, but give a good first approximation for the impulse required by secondary injection or auxiliary motor TVC systems. The perfect autopilot assumption has no appreciable effect upon maximum deflections and impulse.

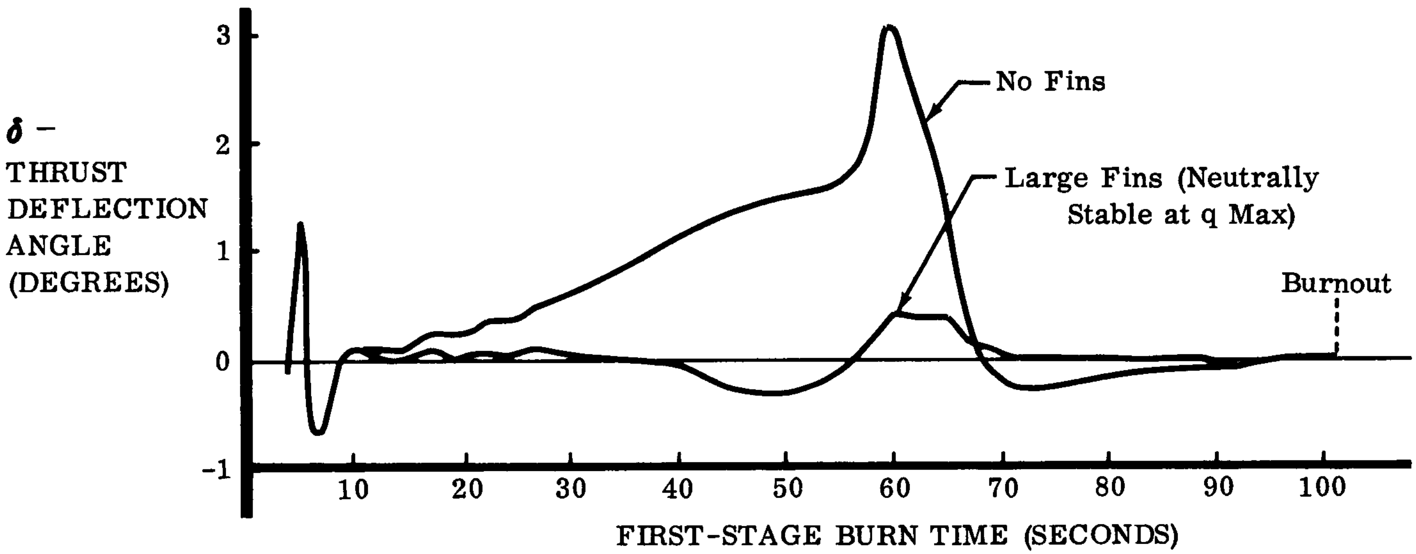
Pitchover is initiated at 4 seconds, and with the present attitude program, 1.28 degrees of thrust deflection are used at this point. Thrust deflection angle builds up with time as the increasing uprange winds of the NASA 99 percent profile are encountered. The wind spike produces an angle of attack of 7.5 degrees at 60 seconds, which is maximum dynamic pressure. This results in a thrust deflection of 3 degrees for the vehicle without fins. The fins for neutral stability at maximum dynamic pressure reduce the thrust deflection required to .4 degrees. Without fins, 1.19 percent of total impulse is used for control in the pitch plane, assuming no misalignments. This is reduced to .21 percent for the vehicle with fins.

Since only .4 degree of thrust deflection is required at maximum dynamic pressure for the vehicle with fins, the tilt maneuver becomes the critical deflection requirement. The tilt deflection, when critical as in this case, can be reduced somewhat by modifying the attitude program.

CONTROL TIME HISTORY
500K Vehicle

- NASA 99% Wind Profile
- Control Frequency = .20 CPS
- Damping Ratio(ζ) = .70
- No Misalignments Included





Percent Side Impulse	
1.19	No Fins
.21	Fins

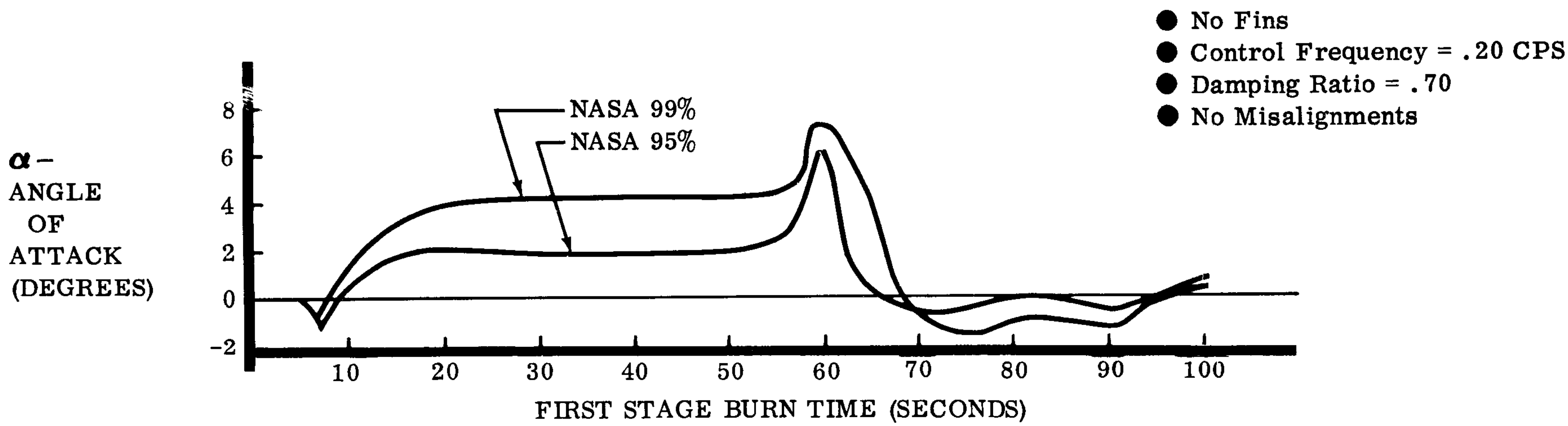
WIND PROFILE EFFECTS

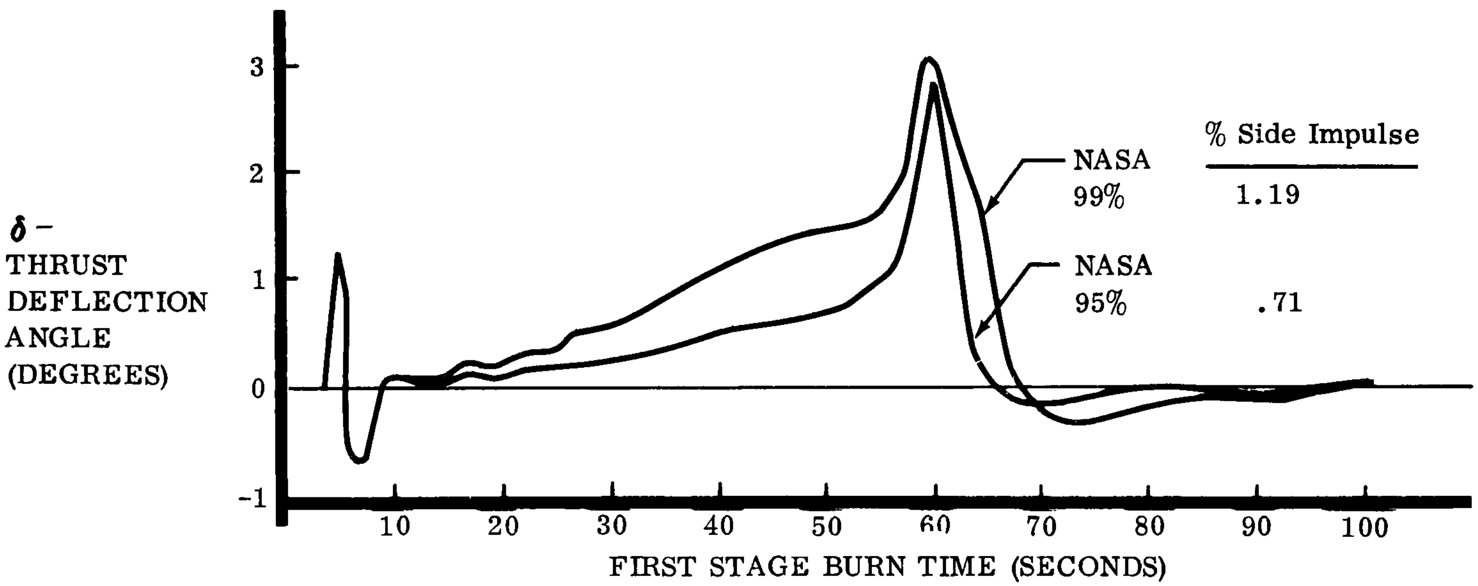
The design wind profile has a strong influence on the vehicle control requirements. A comparison of thrust deflection angle and angle of attack, during first stage boost for the 500K payload vehicle without fins is shown for the NASA 95 percent and 99 percent wind profiles. The 99 percent profile, designated for this study, has a maximum velocity of 318 feet per second as compared with 250 feet per second for the 95 percent profile. Also, at the lower altitudes, the 99 percent profile is much fuller, even through the maximum wind shear values are not much different. Consequently, during the early portion of boost the angle of attack for both profiles remains almost constant, but with a higher value associated with the 99 percent profile. This is the region in which the slope of wind speed versus altitude is constant, demonstrating that angle of attack is proportional to wind shear. The 99 percent profile has a larger angle of attack and hence higher impulse in this lower region. At the wind spike, the two angles of attack are nearly the same because the magnitude of the wind shear for the two spikes is similar.

Thrust deflection angle is higher for the 99 percent profile because the magnitude of the wind speed is larger. Control impulse is 1.19 percent for the 99 percent profile compared to .71 percent for the 95 percent profile.

This data shows that an impulse-designed TVC system (secondary injection or auxiliary motors) is greatly affected by the lower altitude wind profile, while the peak winds, although imposing a slightly higher deflection requirement, do not have too great an effect.

WIND PROFILE EFFECTS





CONTROL REQUIREMENT BREAKDOWN

The control requirements tabulated herein for the two vehicles under study are based on simulation of the longitudinal degrees of freedom during first stage boost, as shown previously, plus analytically determined effects of misalignments and motor variations. Typical breakdowns of the total requirements are shown.

The control requirements for the basic pitchover are determined by simulating first stage boost without any wind disturbances. The requirements associated with the wind are determined using a NASA 99 percent uprange wind profile with the peak of the wind spike at the altitude of maximum dynamic pressure.

The maximum thrust deflection angle required in the pitch control plane is the combination of the misalginment and wind disturbance requirements. The maximum control deflection occurs at maximum dynamic pressure. The wind disturbance is assumed to be 8 percent larger in the yaw plane because the wind is always perpendicular to the vehicle axis, hence the larger deflection angle requirement in the yaw plane.

The pitch and yaw side impulse requirements are combined to form a total boost mission requirement assuming a common impulse source. Without this common source, the twc requirements would have to be summed directly.

The control frequency is larger for the 125K payload vehicle, since the control frequencies were chosen at approximately equal fractions of first-body bending frequency.

The control requirements for the 125K payload vehicle, may increase if it is determined that a lower control frequency must be used to achieve a higher ratio of bending frequency to control frequency.

CONTROL REQUIREMENT BREAKDOWN

NASA 99 Percent Wind Profile (No Fins)

	500K PAYLOAD VEHICLE		125K PAYLOAD VEHICLE	
	Thrust Deflection Angle	Percent Side Impulse	Thrust Deflection Angle	Percent Side Impulse
PITCHOVER	1.28	.12	.42	.05
WIND DISTURBANCE (PITCH PLANE ONLY)	3.05	1.07	2.72	1.08
MISALIGNMENTS	.37	.56	.34	.54
± 4 Percent Thrust Variation				
2 Inch C G Offset From Vehicle Centerline				
± .25° Thrust Vector Variation				
PITCH CONTROL REQUIREMENT	3.42	1.75	3.06	1.67
YAW CONTROL REQUIREMENT	3.67	1.72	3.28	1.71
BOOST MISSION REQUIREMENT With Common Control Impulse Source For Pitch and Yaw	-	2.49	-	2.40
CONTROL FREQUENCY	.20 CPS		.40 CPS	
FIRST BODY BENDING FREQUENCY / CONTROL FREQUENCY	5.8		6.8	

VEHICLE STABILITY EFFECTS

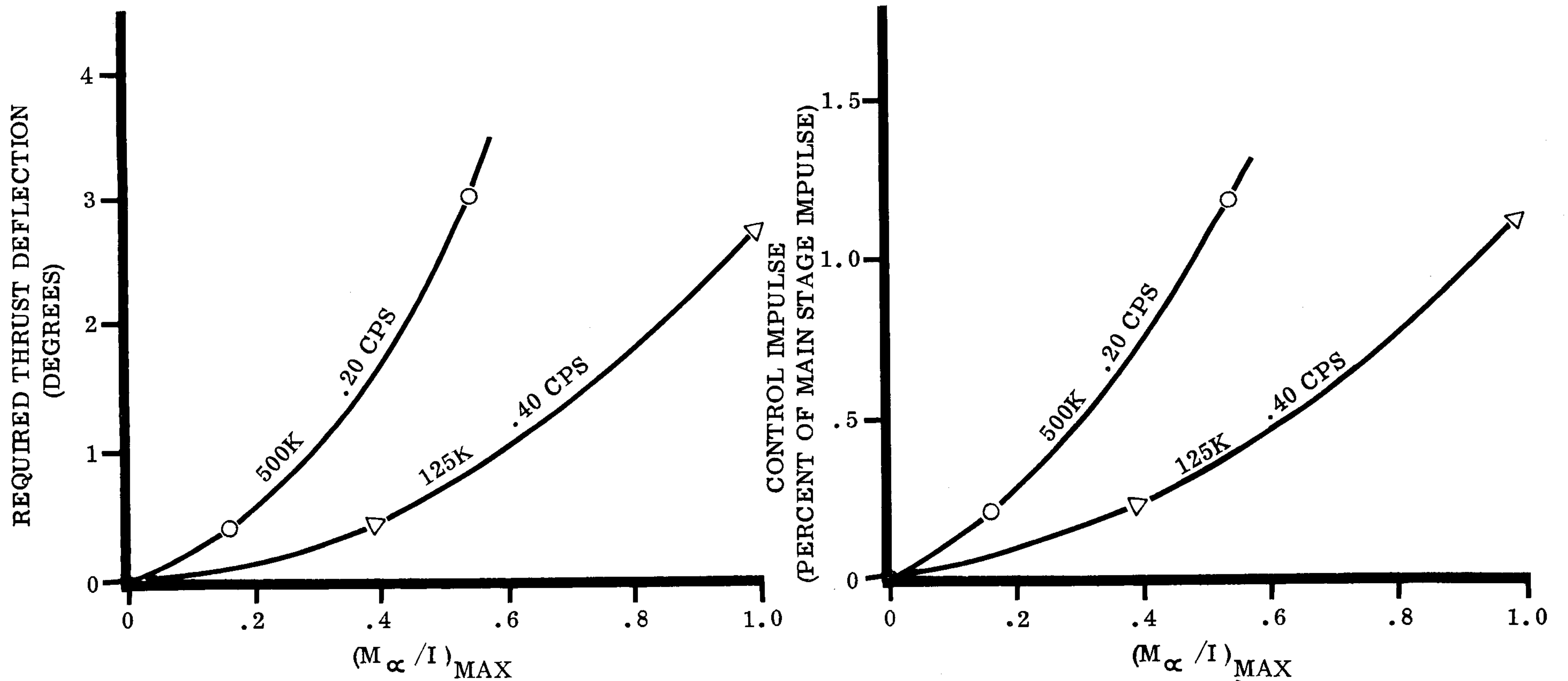
Preliminary parametric control requirement data are shown for variations in vehicle stability and control frequency. The decreasing control requirements with decreasing vehicle instability are clearly evidenced. The difference between the two vehicles is partially due to the difference in trajectory and vehicle size, and partially due to control frequency.

Consideration of an intermediate fin size for both vehicles and employing lower control frequencies for the 125K vehicle will be accomplished to establish a more complete correlation. Completion of this data will allow estimation of control requirements for a range of booster vehicles with similar design specifications.

VEHICLE STABILITY EFFECTS

99 Percent Wind Profile

WIND PLUS DYNAMIC EFFECTS
PITCH PLANE ONLY



CONTROL - FIXED AERODYNAMIC ANGULAR DIVERGENCE $\frac{\text{DEGREES}}{\text{SEC}^2}$ / DEGREE ANGLE OF ATTACK

[redacted]

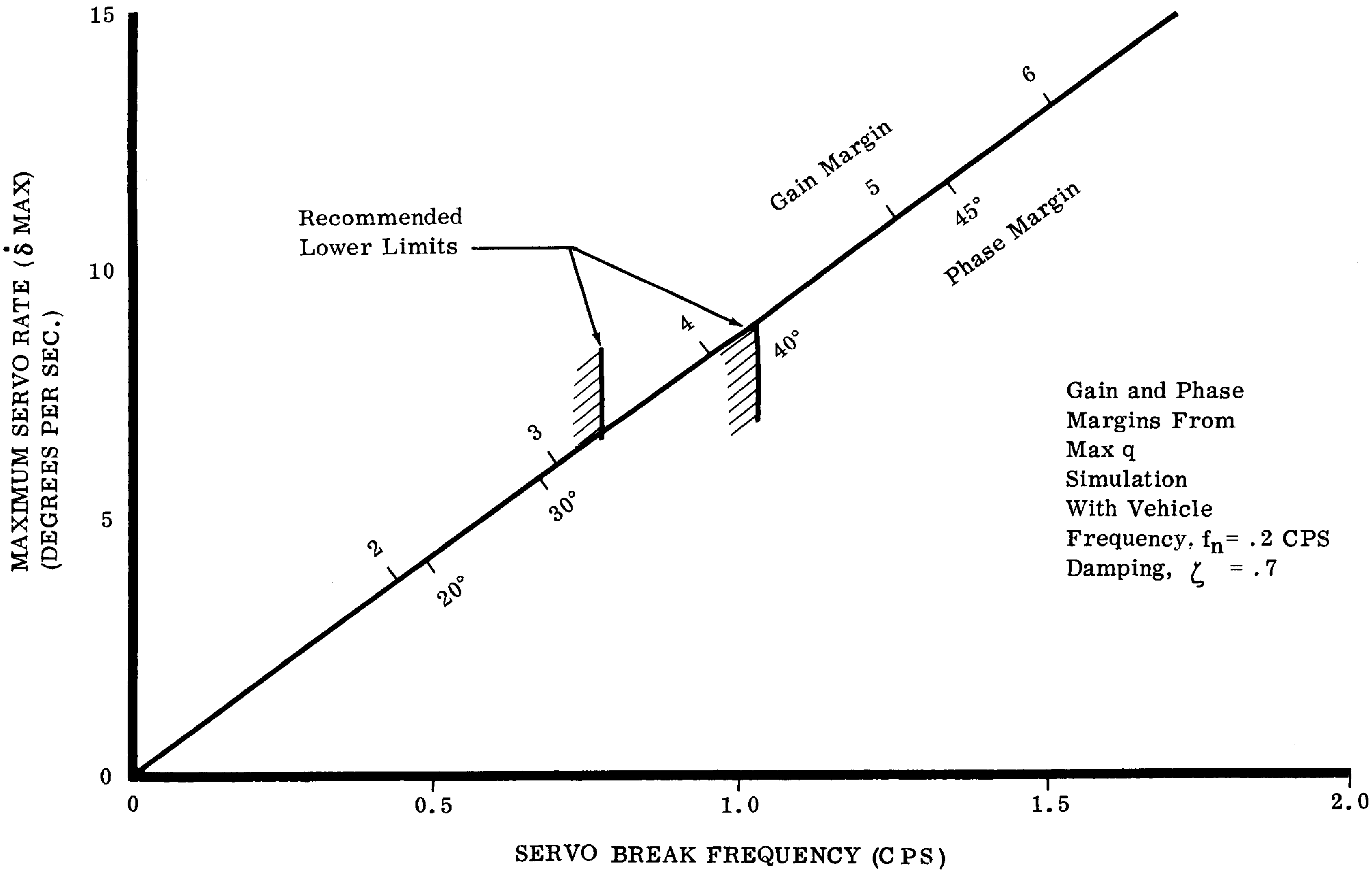
ACTUATION RESPONSE REQUIREMENTS

The design of a TVC system as well as the vehicle response is influenced by the servo actuation frequency. The vehicle response ideally should be determined by the control system gains and be essentially independent of the servo response characteristics. This condition exists when the servo, as represented by a first-order transfer-function, has a break frequency greater than 10 times the short period control frequency. Application of this conservative rule-of-thumb requires high nozzle accelerations and rates and accompanying weight penalties in the servo hardware.

Analytical and analog simulation studies are being carried out to determine minimum actuation break frequency that will minimize TVC power requirements without degrading the vehicle response. These analyses of the vehicle indicate that a lower value of servo frequency may be acceptable. The chart showing the relationship between maximum servo rate and servo frequency indicates typical values of gain and phase margins. Good design practice specifies minimum values of 3.2 (10 db) for the gain margin and 40 degrees for the phase margin. The data indicates that these conditions can be satisfied with a servo break frequency of about one cycle-per-second.

ACTUATION RESPONSE REQUIREMENT

500K Vehicle



STAGE SEPARATION SEQUENCE

Stage separation studies of the 500K vehicle are being carried out to establish control requirements, staging dynamics, engine tail-off characteristics, and the overall sequence considering all disturbances and motor variances.

Preliminary stage separation studies have been based on thrust-time histories and have resulted in the indicated sequence.

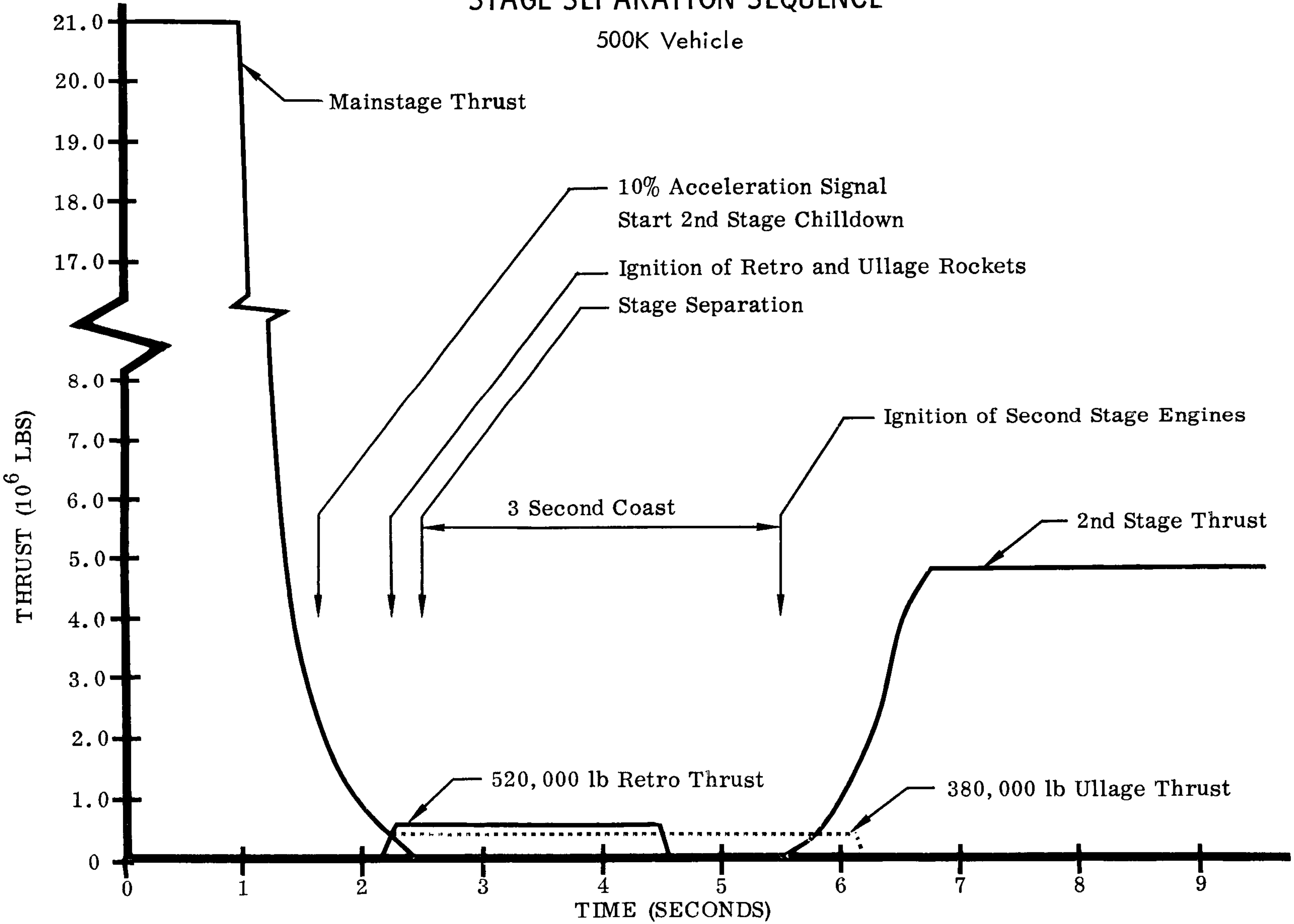
The sequence is initiated by an acceleration switch, triggered when thrust has decayed to 10 percent of the nominal value. Retro and ullage rockets are ignited at this time. Thrust vector control is required during the solid-motor thrust tail-off.

The abrupt thrust decay requires a retrothrust of 520,000 pounds to achieve a 0.5-g retrograde acceleration of the empty first stage. The ullage thrust required to provide 0.1-g posigrade acceleration of the upper stage vehicle is 380,000 pounds. This preliminary sequence utilizes a three-second coast time to accommodate a conventional chilldown procedure for the M-1 engines and to allow for reasonable spacing of booster and second stage when the engines are ignited.

The major solid-booster dynamics problems being studied include determination of required nozzle-cant angle, establishment of angular motions before and after stage separation due motor variances, and clearance between the two stages.

STAGE SEPARATION SEQUENCE

500K Vehicle



[redacted]

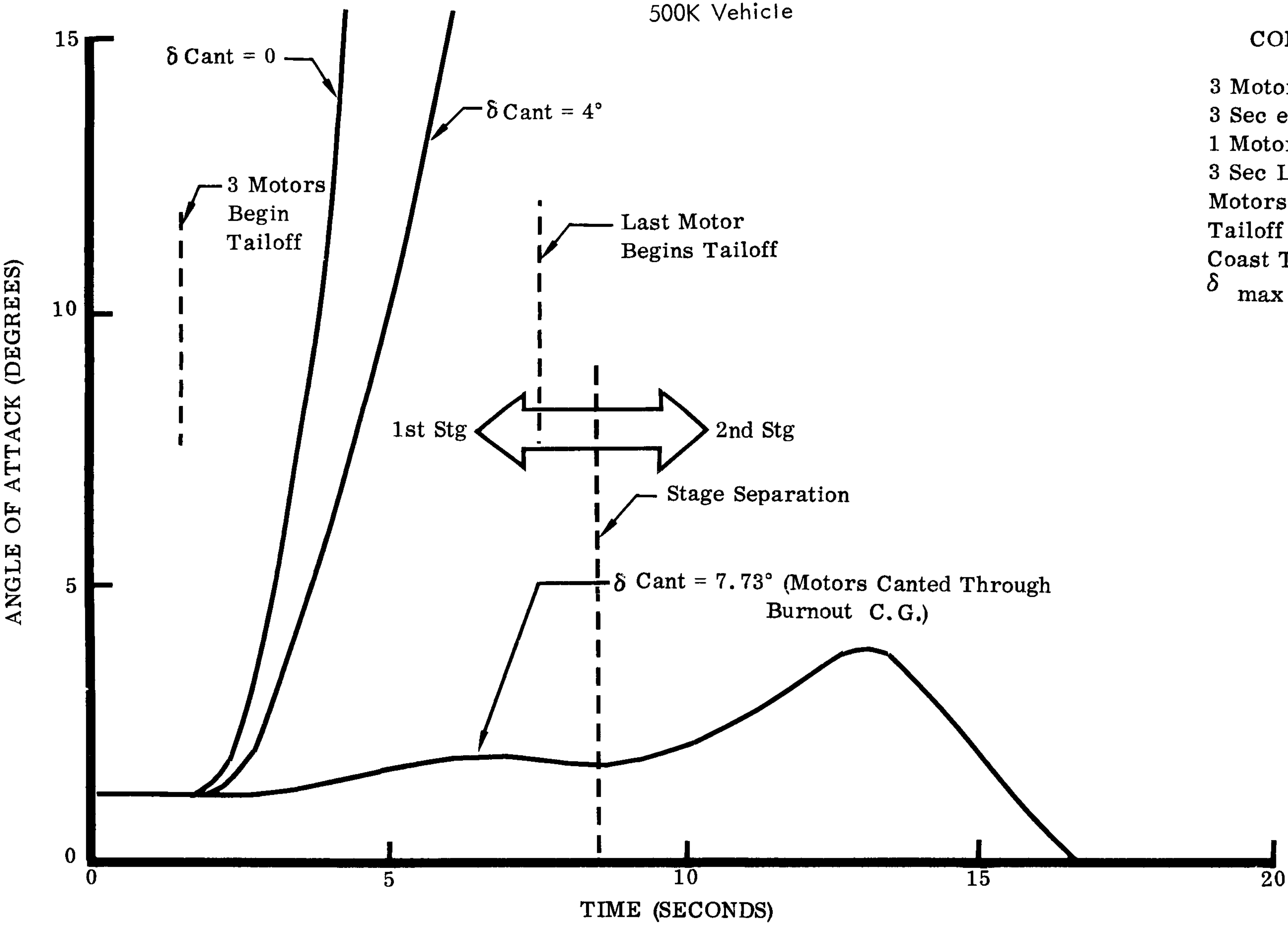
MOTOR CANTING AT STAGE SEPARATION

One of the stage-separation control problems is variance in burn time for the solid motors. Nozzle canting is required to reduce overturning moments. Of all possible variations, the worst control case occurs when three motors burn out early and one motor is late. A burn-time variance for the 500K payload vehicle of ±3 percent of the nominal burn time is assumed.

The following plot shows the results of a missile angle-of-attack simulation when the 3-and-1 split occurs with ±3 percent burn-time variance. Conditions of no canting, canting through the burnout center of gravity, and an intermediate case are shown. The data indicate that little reduction in cant angle from the center-of-gravity location can be tolerated without incurring excessive angles of attack.

MOTOR CANTING AT STAGE SEPARATION

500K Vehicle



CONDITIONS

3 Motors Burn Out
3 Sec early
1 Motor Burns Out
3 Sec Late — (All
Motors Have 1 Sec
Tailoff Time,
Coast Time = 3 Sec)
$\delta_{max} = \pm 4°$

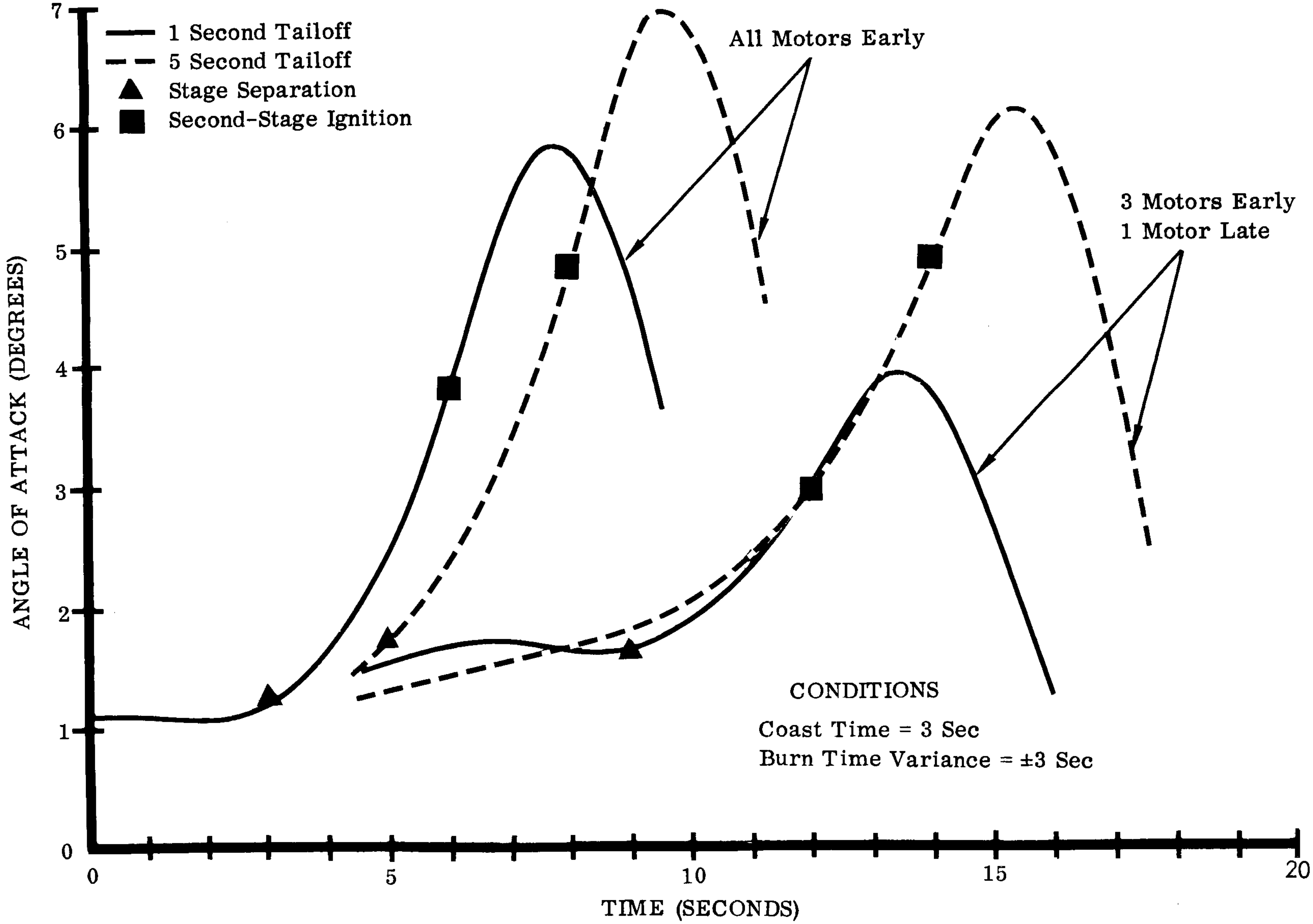
ANGLE OF ATTACK DURING COAST

500K Vehicle

Investigations of the dynamic motion of the first and second stages during stage separation are made to determine the critical motor variance conditions for control. The chart shows first- and second-stage angle of attack for the motor burn-time variances of all motors burning out early, and three motors burning out early with one late. The higher dynamic pressure at the trajectory point of all motors burning out early is more critical than the unequal thrust of the three early, one late. Motors are assumed canted through the burnout center of gravity. The five-second tail-off results in a greater angle-of-attack excursion, but additional calculations are required for long tail-off times to determine the most critical.

ANGLE OF ATTACK DURING COAST

500 K Vehicle



ALLOWABLE COAST TIME

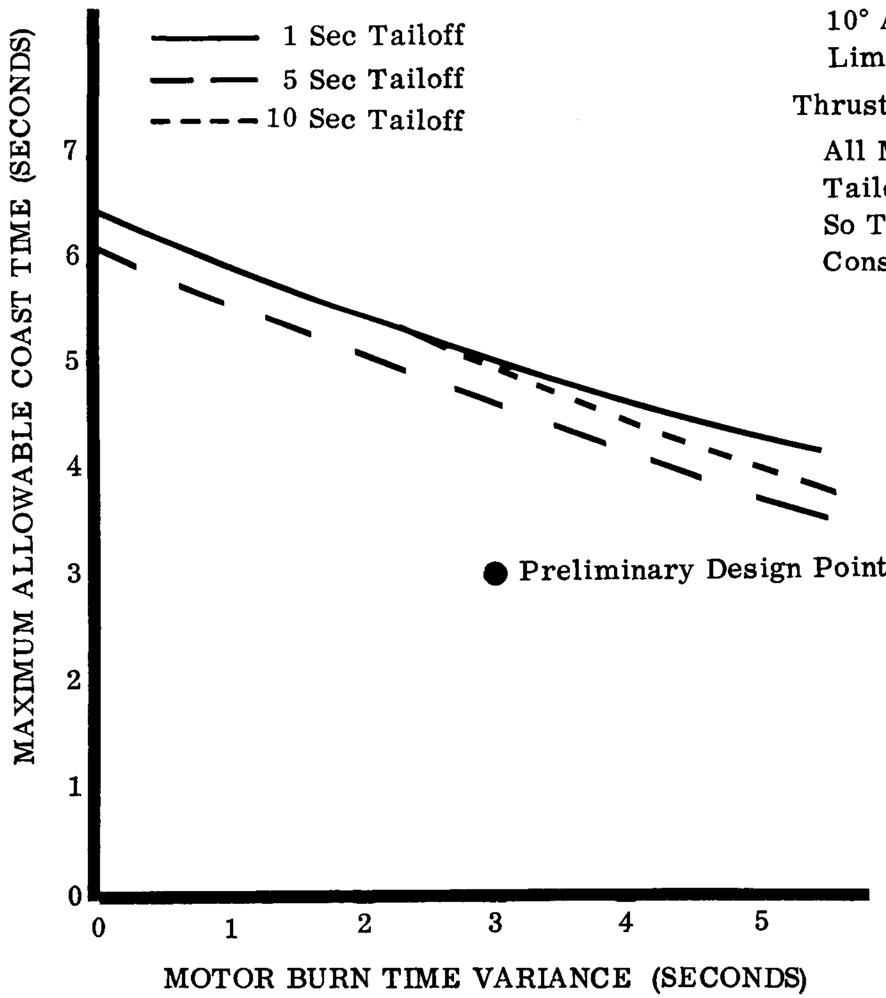
500K Vehicle

A moderate coast after stage separation is desirable to accommodate the upper-stage engine starting sequence and to allow adequate clearance between stages before upper-stage engine ignition. The upper-stage angle of attack must remain within reasonable limits so that after ignition the second-stage engines can gain control of any angular divergence incurred during uncontrolled coast. Studies of maximum allowable coast time are shown as a function of solid-stage tail-off and motor burn-time variances. A maximum angle of attack of 10 degrees is used as the limiting criteria.

The burn-time variance has the greatest effect on allowable coast time, but calculations are being made for longer tail-off times to provide complete coverage of this parameter.

ALLOWABLE COAST TIME

500 K Vehicle



CONDITIONS

Max Coast Time Basis:

10° Angle-of-Attack Limit

Thrust Decay Basis:

All Motors Out Early, Tailoff Time Varies So Total Impulse Constant For all Cases

BLANK

TVC SYSTEM STUDIES

W G. Nelson
Bill

BLANK

TVC SYSTEM STUDIES

Initial steps taken to provide parametric TVC system data and to select the optimum systems for each of the two study vehicles consisted of the following items:

1) Release of a TVC system state-of-the-art document (D2-20768) on existing production systems.

2) Review of past applicable TVC system study efforts by other companies.

3) Survey trip to five TVC component or solid-motor suppliers.

The next task was to develop parametric data useful to trade studying of large TVC systems and to study the effects of variations in TVC system requirements on the selection of a specific type of control system. This task is continuing throughout the program. A number of the subsequent charts provide examples of the parametric data accumulated to date.

Preliminary requirements for both vehicles were established at this point in the program and a detail trade study of 10 TVC systems versus these requirements was undertaken.

A review of weight studies, actuator or injection valve flow requirements, system complexity and component size variations as shown by configuration layouts, and other trade parameters was made to select the best candidates for detail study.

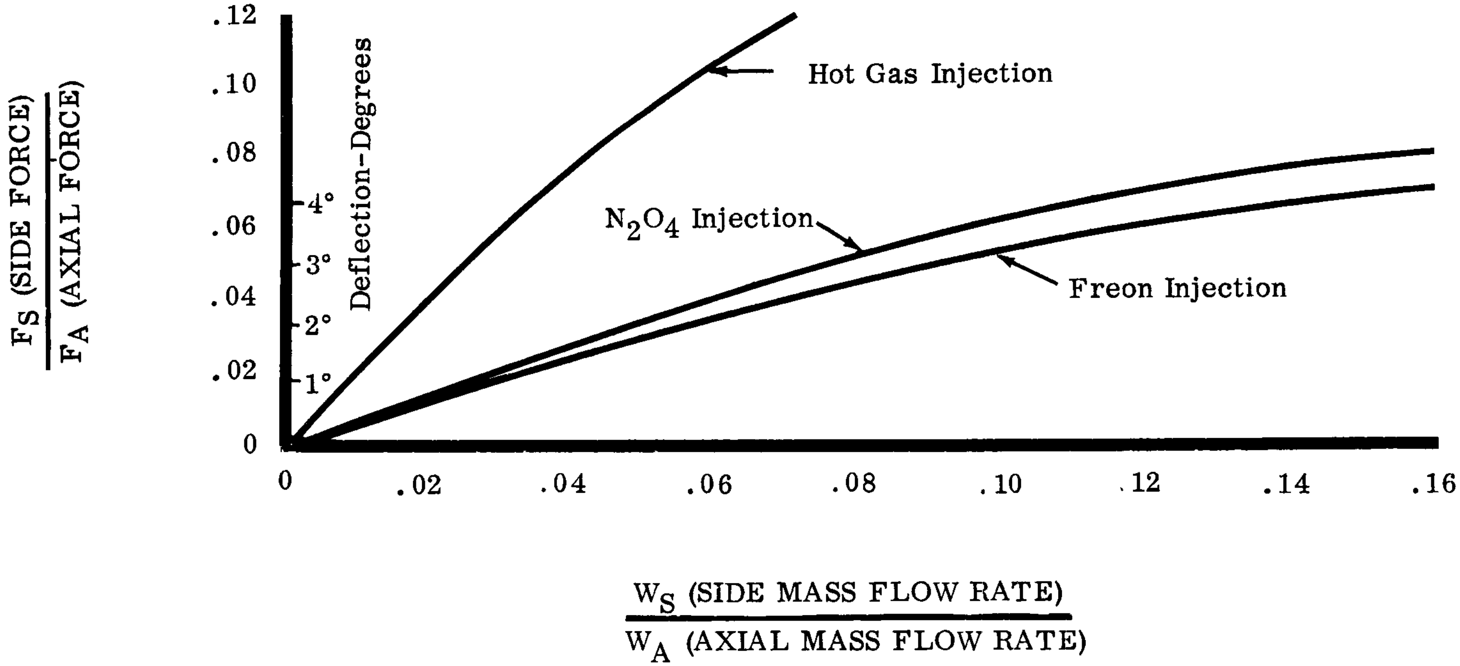
INJECTION SYSTEM FLOW CHARACTERISTICS

An example of significant parameters relating to the application of fluid-injection-type TVC systems is shown.

A thrust ratio of side force to axial force is plotted against a side to axial mass flow ratio for three injectants: hot gas, N_2O_4, and Freon 113. Linearity problems that require changes in control system gain are reflected by the deviation from a straight line. The much earlier saturation limit of liquid injection systems versus hot gas systems is also demonstrated.

Side force ratios for the 125K and 500K vehicles being studied fall in the .01 to .025 region, the most linear portion of the curves.

INJECTION SYSTEM FLOW CHARACTERISTICS



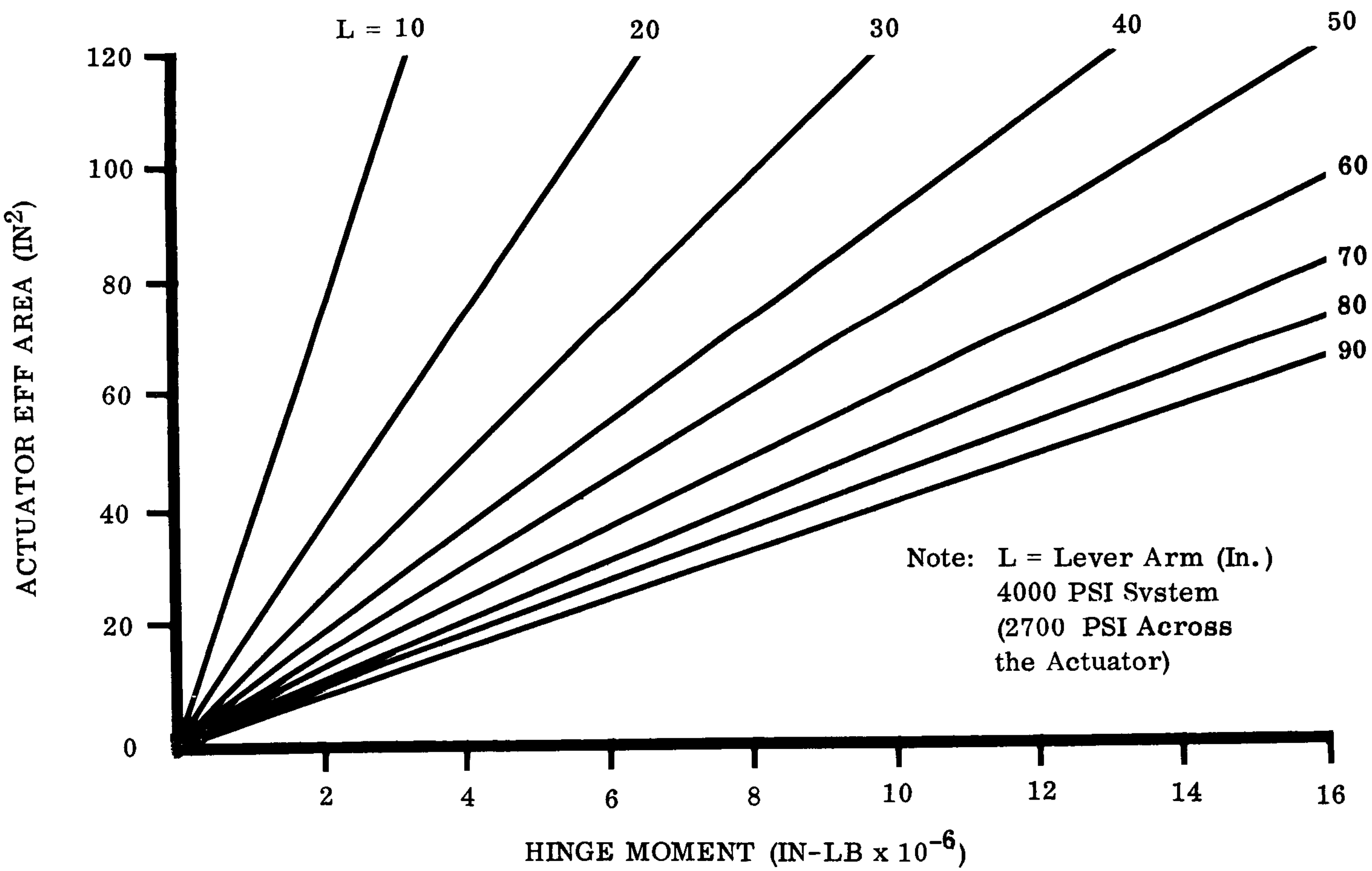
HINGE MOMENT VARIATIONS

Movable Nozzle

These plots for the given system pressure of 4000 psi show the effects of lever arm changes on actuator cylinder area for specific hinge moments. As the lever arm is increased for a given hinge moment, the actuator effective cylinder area is decreased, thus decreasing the actuator weight. (The change in effective cylinder area affects actuator weight to a much greater degree than the corresponding change in piston stroke.)

The reduction in actuator weight due an increased lever arm is somewhat offset by the added structure necessary to accommodate the longer lever arm.

HINGE MOMENT VARIATIONS — MOVABLE NOZZLE



GIMBALED NOZZLE HINGE MOMENTS

One of the main performance requirements for movable nozzle-type systems is a definition of hinge moments. Shown are hinge moments for the two study vehicles versus various thrust deflection requirements.

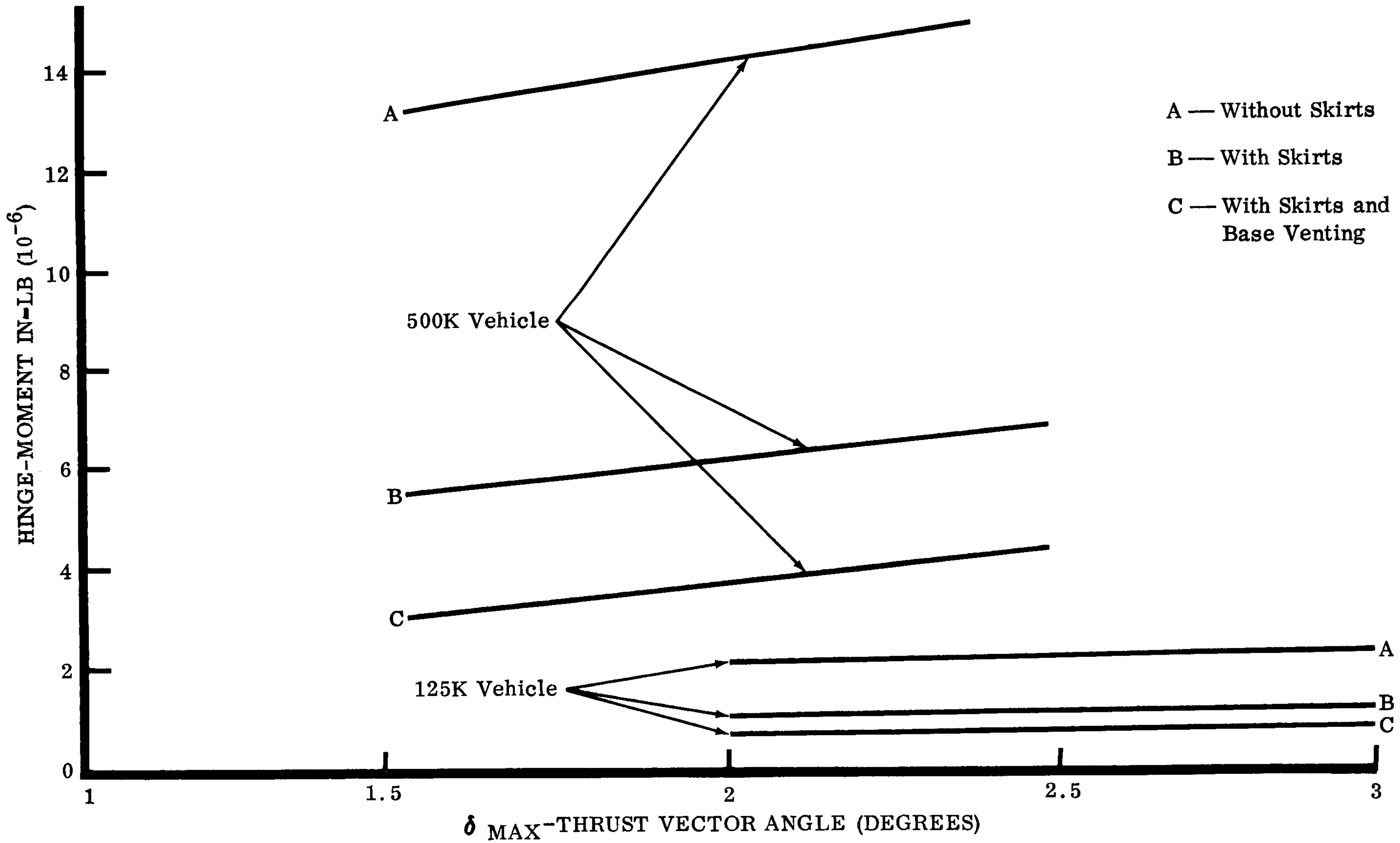
The maximum nozzle hinge moment is the result of a combination of static and dynamic components. The static components, which infer a steady-state servo-force requirement, are the result of vehicle longitudinal acceleration on a canted nozzle and a pressure differential across each nozzle due to aerodynamic effects. The dynamic components are made up of the linear effects of rotational inertia, coriolis damping, and aerodynamic spring-type moments along with the nonlinear effect of coulomb friction that is essentially constant with any movement.

The curves show the hinge moments encountered by the actuation system when the nozzles are actuated in a radial direction. Actuation in a tangential direction involves somewhat smaller hinge-moment loads.

The difference in hinge-moment magnitudes between the A, B, and C curves is the result of changing the nozzle-base pressure distribution with the addition of skirts and venting. It is apparent that the skirts effect a substantial reduction in pressure differential across the nozzles and that the further addition of base venting effects a smaller improvement. As a result, it was recommended that skirts, but not base venting, be employed on the study vehicles.

[redacted]

GIMBALED NOZZLE HINGE MOMENTS



[redacted]

TVC SYSTEM WEIGHT VARIATIONS

500K Vehicle

The curves presented reflect the effects on the weight chargeable to TVC of variations in the system requirements caused by the addition of fins which result in a reduction of deflection and side impulse requirements. The reduction in TVC system weight caused by hinge-moment reductions through the use of skirts and base venting is also shown for the movable nozzle systems with curves A, B, and C.

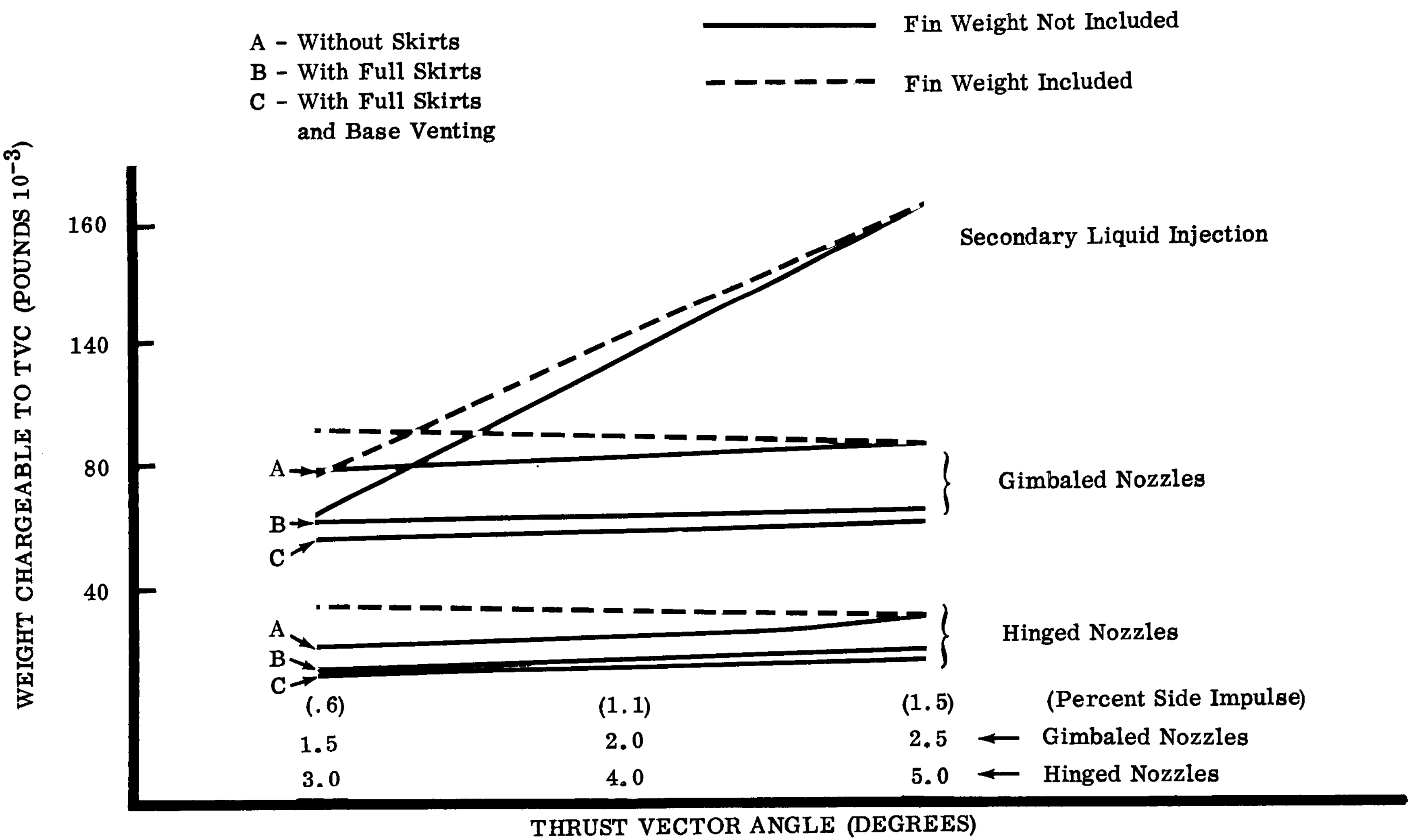
Of significance in these curves is that the weight chargeable to the secondary liquid-injection system increases considerably as the percent-side-impulse requirement is increased.

The curves also show the independence of weight chargeable to either the gimbaled or hinged-nozzle systems with variations in requirements.

The upper requirements of 2.5-degree deflection for a gimbaled system together with 1.5 percent side impulse were assumed for a vehicle without fins. The dashed curves reflect the additional weight of the fins that is necessary to provide the reductions shown in TVC system requirements.

TVC SYSTEM WEIGHT VARIATIONS

500K Vehicle



NOZZLE-ACTUATION FLOW RATES

Movable Nozzles 500K Vehicle

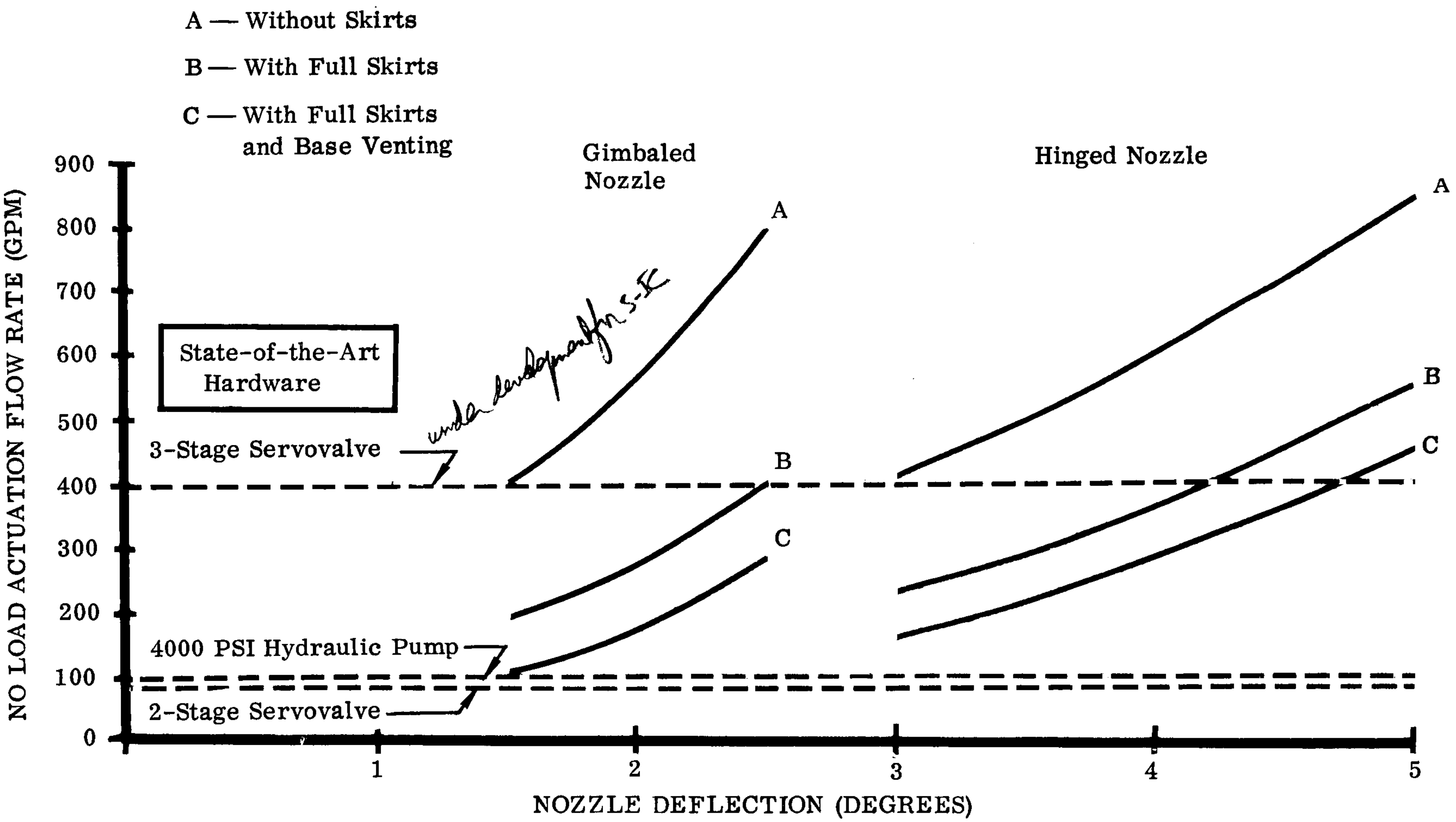
These curves show actuation equipment flow-rate requirements in gallons per minute as a function of control system deflection requirements. The reduction in nozzle deflection requirements implies the addition of fins to the vehicle. The significance of the flow rates for each system is reflected by the flow rate values associated with state-of-the-art hardware. Present two-stage servovalves or 4000 psi hydraulic pumps, for instance, have maximum capabilities of approximately 100 gallons per minute. A larger three-stage valve which is presently under development is not expected to be flight rated for some time. As a consequence, the need for paralleling pumps and/or valves to attain desired flow rates results in increased complexity and is almost certain to degrade reliability. The flow rates plotted are for each of the nozzles on the vehicle.

The effects of reductions in hinge moments through the use of skirts and/or base venting is shown by curves A, B, and C.

ACTUATION FLOW RATES

Movable Nozzle

500K Vehicle



AUXILIARY MOTOR "VECTROL" SIZING

500K Vehicle

These curves reflect the sizing problem associated with one type of auxiliary motor system — "Vectrol" solid motors. Motor diameter is shown versus auxiliary motor deflection for certain vehicle requirements.

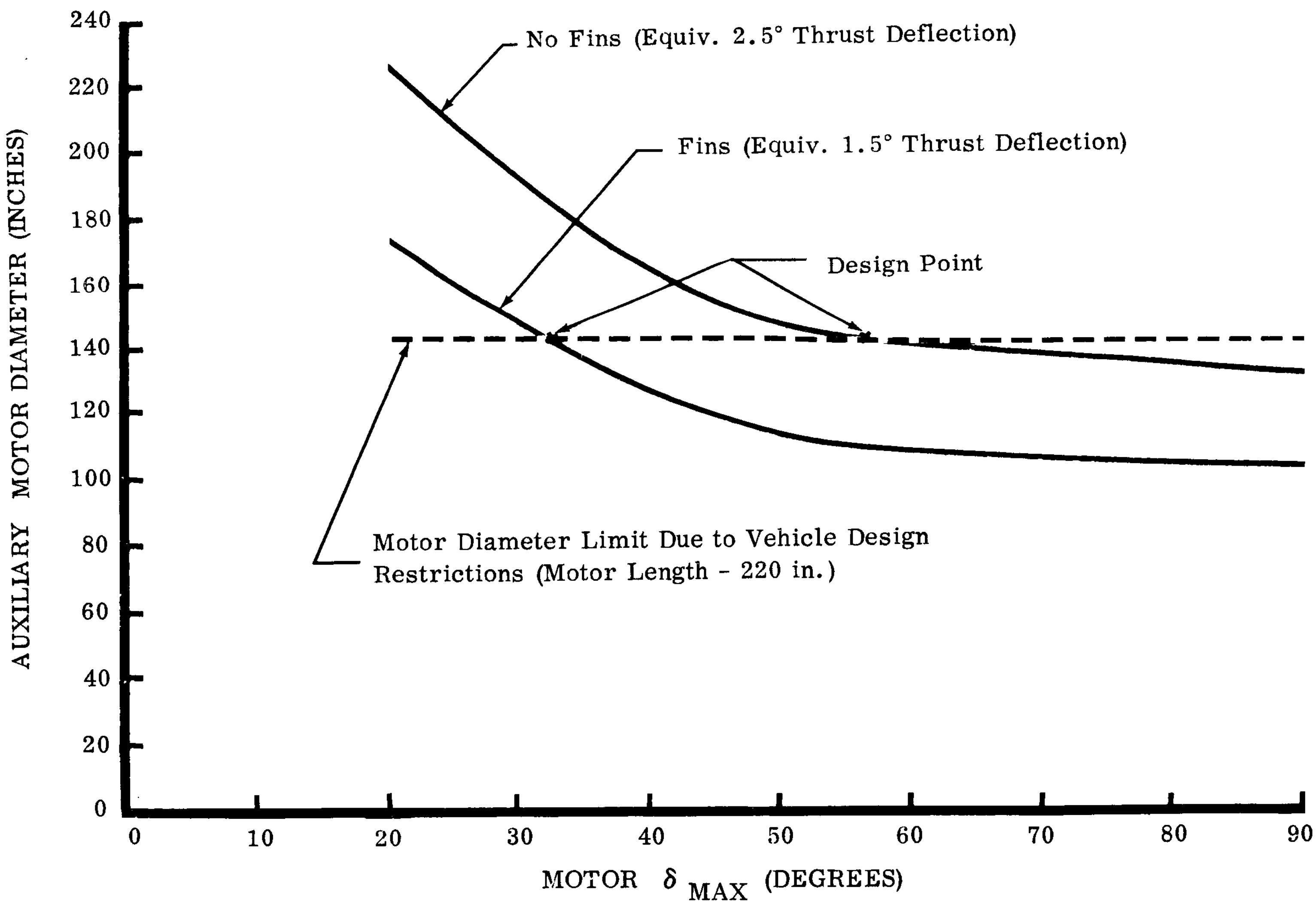
A geometric limitation for the particular study vehicle is shown. This limitation presents design points for the vehicle with and without fins. These design points provide for minimum power systems associated with rotating the "Vectrol" motors.

The four "Vectrol" motors extend radially from the center of the vehicle to the vehicle skirt and their size is governed by the diameter of the vehicle and the clearance between the main vehicle nozzles.

The minimum angle through which the "Vectrol" motors can be rotated is 57.3° for the 500K vehicle without fins and 33.0° for the 500K vehicle with fins.

AUXILIARY MOTOR "VECTROL" SIZING

500K Vehicle



HORSEPOWER REQUIREMENTS
AUXILIARY MOTOR "VECTROL" ACTUATION SYSTEM

500K Vehicles

These curves show that the actuation system horsepower requirements increase with an increase in actuation characteristic frequency and/or an increase in the maximum angle (δ_{max}) through which the "Vectrol" motor is rotated.

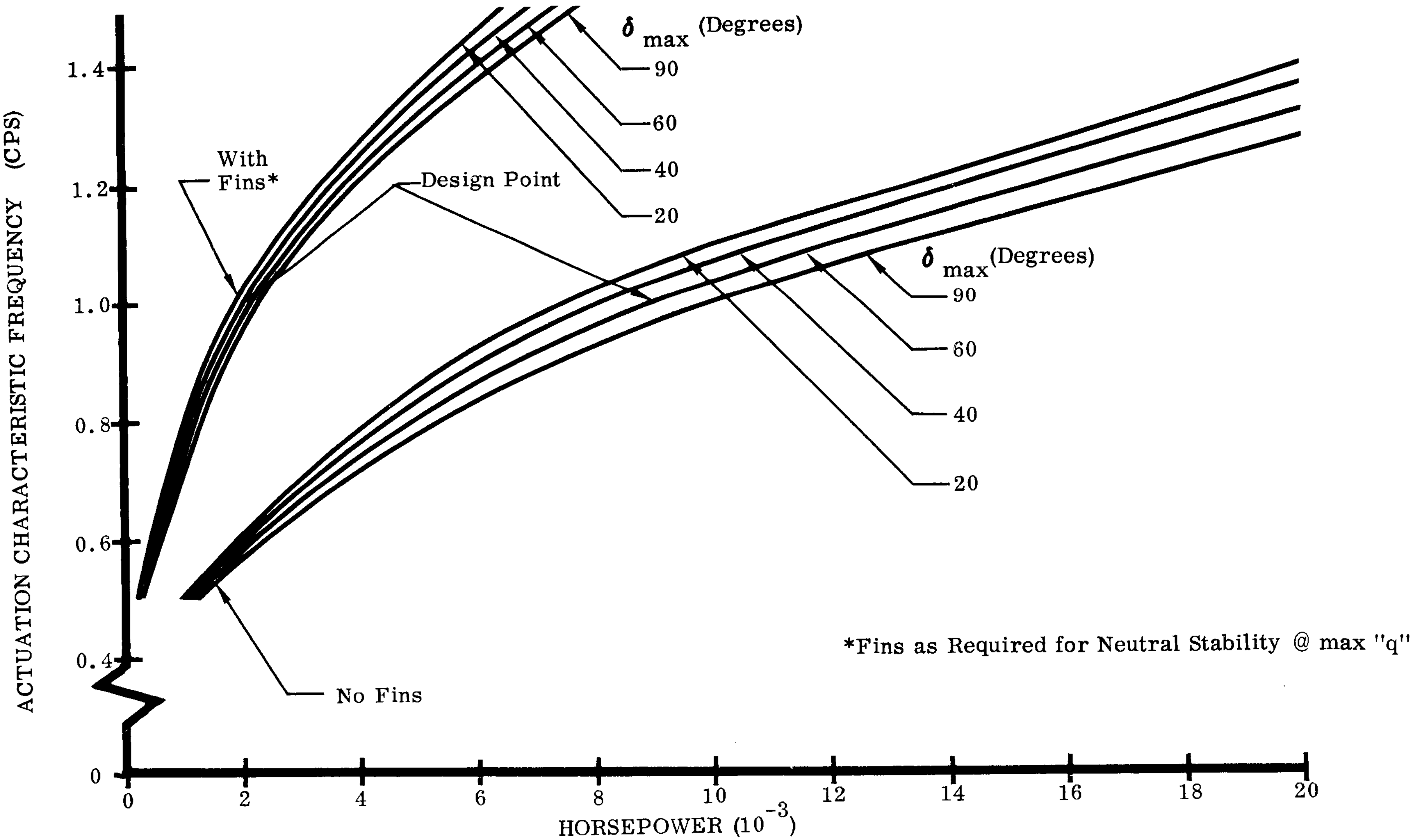
The actuation characteristic frequency design point is 1.0 cycles per second, five times the vehicle control frequency. The actuation system horsepower requirements are 9000 horsepower for the 500K vehicle without fins and 2000 horsepower for the 500K vehicle with fins.

The horsepower requirement is a function of the product of the frequency cubed, the δ_{max} squared, and the motor mass-moment inertia.

HORSEPOWER REQUIREMENTS

Auxiliary Motor "Vectrol" Actuation System

500K Vehicle



SUMMARY OF TVC SYSTEM REQUIREMENTS

This chart summarizes the vehicle control requirements associated with trade studies of the ten TVC systems previously mentioned. Side impulse, actuation frequency, deflection, vector velocity and acceleration, and hinge-moment requirements are listed for the fin and no-fin configurations of the 125K and 500K vehicles. The maximum fins provide for neutral stability at maximum "q."

Only omni-axis requirements for deflection, velocity, and acceleration are listed. The single-axis requirements for these particular parameters are double the values shown.

SUMMARY OF TVC SYSTEM REQUIREMENTS

*Omni-Axes Only

125K Vehicle	*Max Fins	*No Fins
Percent Side Impulse (Combined)	1.55	2.32
Actuation Frequency	2.0 CPS	2.0 CPS
Max Deflection (δ)	2.0°	3.5°
Max Vector Velocity	13.2°/Sec	26.4°/Sec
Max Vector Acceleration	2.9R/Sec^2	5.8R/Sec^2
Max Hinge-Moment: Radial	.88(10^6) In/Lb	1.081(10^6) In/Lb
Tangential	.868(10^6) In/Lb	1.063(10^6) In/Lb

500K VEHICLE		
Percent Side Impulse (Combined)	1.07	2.0
Actuation Frequency	1.5 CPS	1.5 CPS
Max. Deflection (δ)	1.5°	2.5°
Max Vector Velocity	6.6°/Sec	13.2°/Sec
Max Vector Acceleration	1.085R/Sec^2	2.17R/Sec^2
Max Hinge-Moment: Radial	4.856 (10^6) In/Lb	5.943 (10^6) In/Lb
Tangential	3.423 (10^6) In/Lb	4.477 (10^6) In/Lb

TVC SYSTEMS EVALUATED

This chart lists the ten TVC systems that were evaluated against specific requirements for each of the vehicles. The systems were chosen mainly on the basis of unquestionable feasibility and state-of-the-art experience.

In Category I, movable nozzle systems, both hinged and gimbaled nozzle systems, were considered along with two types of power systems. The 4000-psi closed-loop hydraulic system is powered by solid-propellant gas-turbine-driven pumps. The 2000-psi open-loop hydraulic system is of the blowdown variety with a solid propellant providing pressurization for a large reservoir of fluid.

Both liquid and solid reaction motors were considered in Category II, auxiliary motor systems. The liquid system is a hypergolic, bipropellant system with individual on-off control of eight segments in each of the four reaction motors, which are fixed with a line of thrust perpendicular to the main thrust. The solid-motor system is patterned after the Allison "Vectrol" system. The drive system for each "Vectrol" consists of a hydrazine-powered gas turbine driving hydraulic pumps. The pumps supply hydraulic fluid to servo actuated rotary drives geared to the "Vectrol" motors.

Three types of fluid injection systems were considered in Category III: a nonreactive Freon 113 system, a reactive N_2O_4 system, and a reactive bipropellant system using N_2O_4 and Aerozine (50 percent hydrazine plus 50 percent UDMH).

In the fourth category of combination systems, only one typical system was considered — a jetavator control and N_2O_4 injection combination. Secondary injection was utilized for 70 percent of the TVC duration, with jetavators used to satisfy the higher deflection requirements throughout the boost phase of flight.

TVC SYSTEMS EVALUATED

CATEGORY I	Hinged Nozzle	— 4000 PSI Hydraulic	Closed Loop
	Hinged Nozzle	— 2000 PSI Hydraulic	Open Loop
	Gimbaled Nozzle	— 4000 PSI Hydraulic	Closed Loop
	Gimbaled Nozzle	— 2000 PSI Hydraulic	Open Loop
CATEGORY II	Auxiliary Motor	N_2O_4 (50-50) Reaction Motor	
	Auxiliary Motor	"Vectrol" Solid Reaction Motors	
CATEGORY III	Fluid Injection	— N_2O_4	
	Fluid Injection	— Freon 113	
	Fluid Injection	— N_2O_4 (50-50) Hydrazine + UDMH	
CATEGORY IV	Combination System	— Jetevator and N_2O_4 Injection	

TVC WEIGHT PENALTY ON PAYLOAD

500K Vehicle

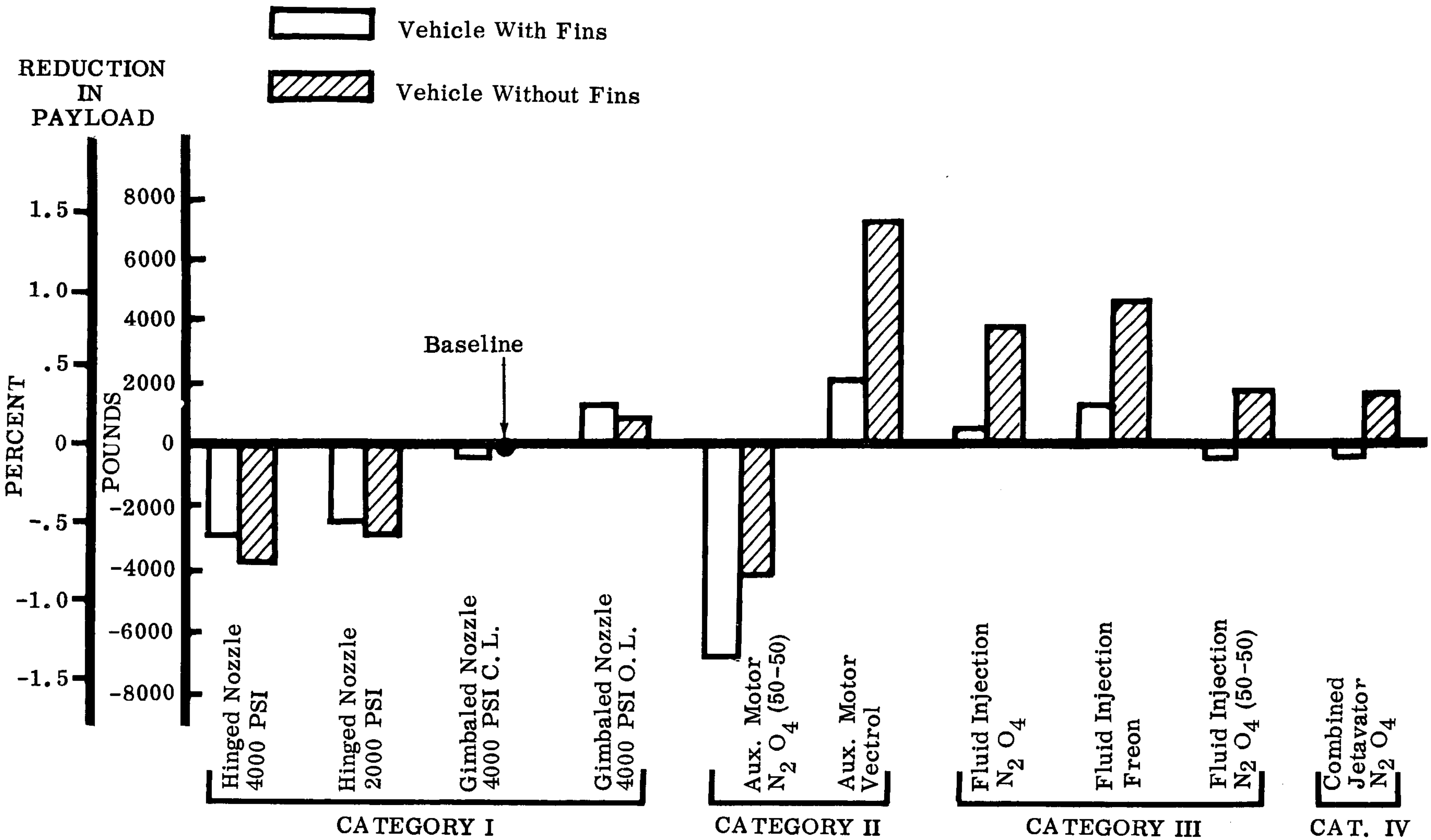
The reduction in payload effected by the addition of a TVC system to the baseline vehicle is shown for each of ten systems. The baseline vehicle is assumed to have a gimbaled nozzle TVC system and no fins. The addition of maximum fins indicates a substantial weight saving for systems utilizing expending fluid. The most significant payload weight advantage is reflected in the use of the bipropellant liquid reaction control system. This is due to the overall effect of eliminating the main motor cant angle along with the reduction in requirements associated with the addition of fins.

Movable nozzle systems realize little, if any, benefit from the addition of vehicle fins since the added fin weight approximately equals the savings in TVC hardware weight.

Payload reductions in weight are directly related to TVC system equivalent weight. TVC equivalent weight is that theoretical fixed weight used to replace the initial TVC system weight in order to produce an equal burnout velocity for the evaluation of different TVC systems.

TVC WEIGHT PENALTY ON PAYLOAD

500 K Vehicle



VALVE FLOW-RATE REQUIREMENTS

500K Vehicle

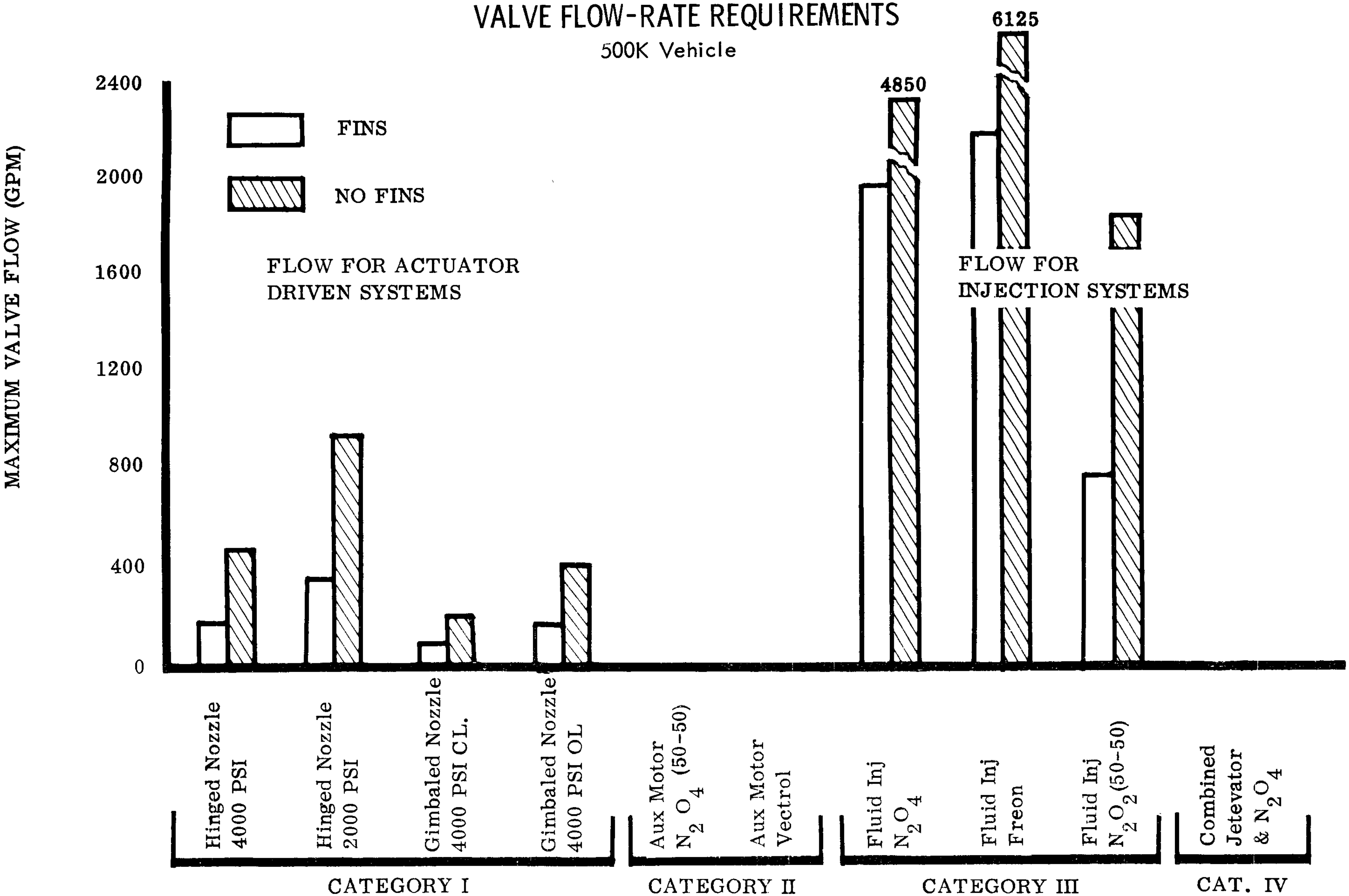
Maximum pitch valve flow for one main motor nozzle is shown related to eight of the ten evaluated systems.

The effect of adding maximum fins to the vehicle reduces the thrust vector control required and, thus, reduces the necessary flow by a substantial amount. In the case of movable nozzle systems, the addition of fins reduces the valve flow requirements to within present state-of-the-art hardware capability. Similarly, in the case of injection systems, the addition of fins reduces the injected flow requirements below the maximum flows programmed during past large solid-motor test firings.

CONFIDENTIAL

VALVE FLOW-RATE REQUIREMENTS

500K Vehicle



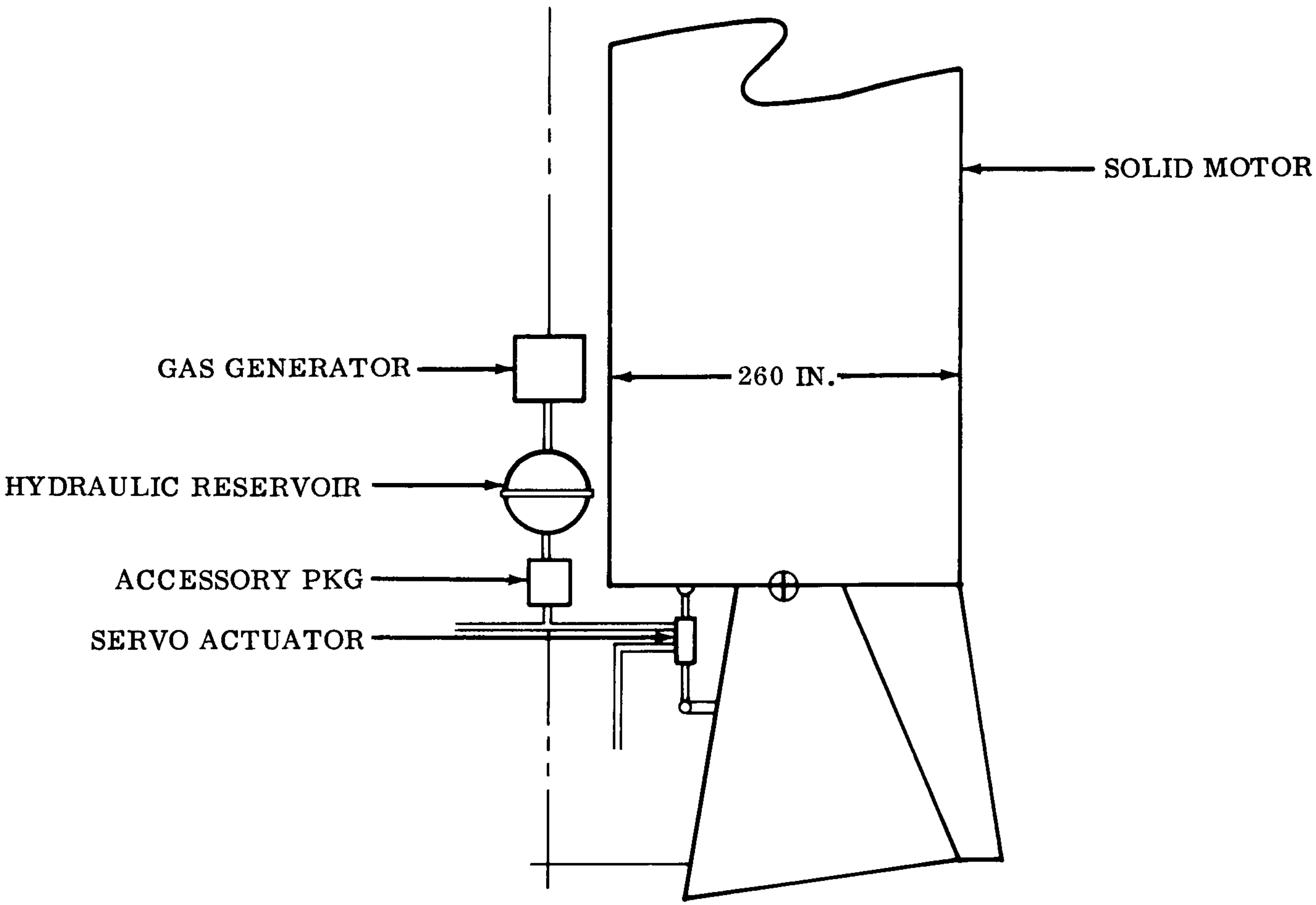
TVC SYSTEMS

HINGED NOZZLE — EXPANDING FLUID

The complexity and relative sizes of TVC components are shown for a hinged-nozzle expanding-fluid system. Two of the four hinged nozzles vector in each control plane, in contrast to the gimbaled system shown on the next chart in which all four nozzles vector in both planes.

The actuation system pictured with the hinged nozzles is the least complex of the linear actuation systems. The fluid is pressure fed by a slow-burning solid-propellant gas generator to a hydraulic reservoir and controlled by a servoactuator mechanism. Used fluid is jettisoned.

HINGED NOZZLE
Expanding Fluid
(500K Vehicle)



GIMBALED NOZZLE — RECIRCULATING FLUID

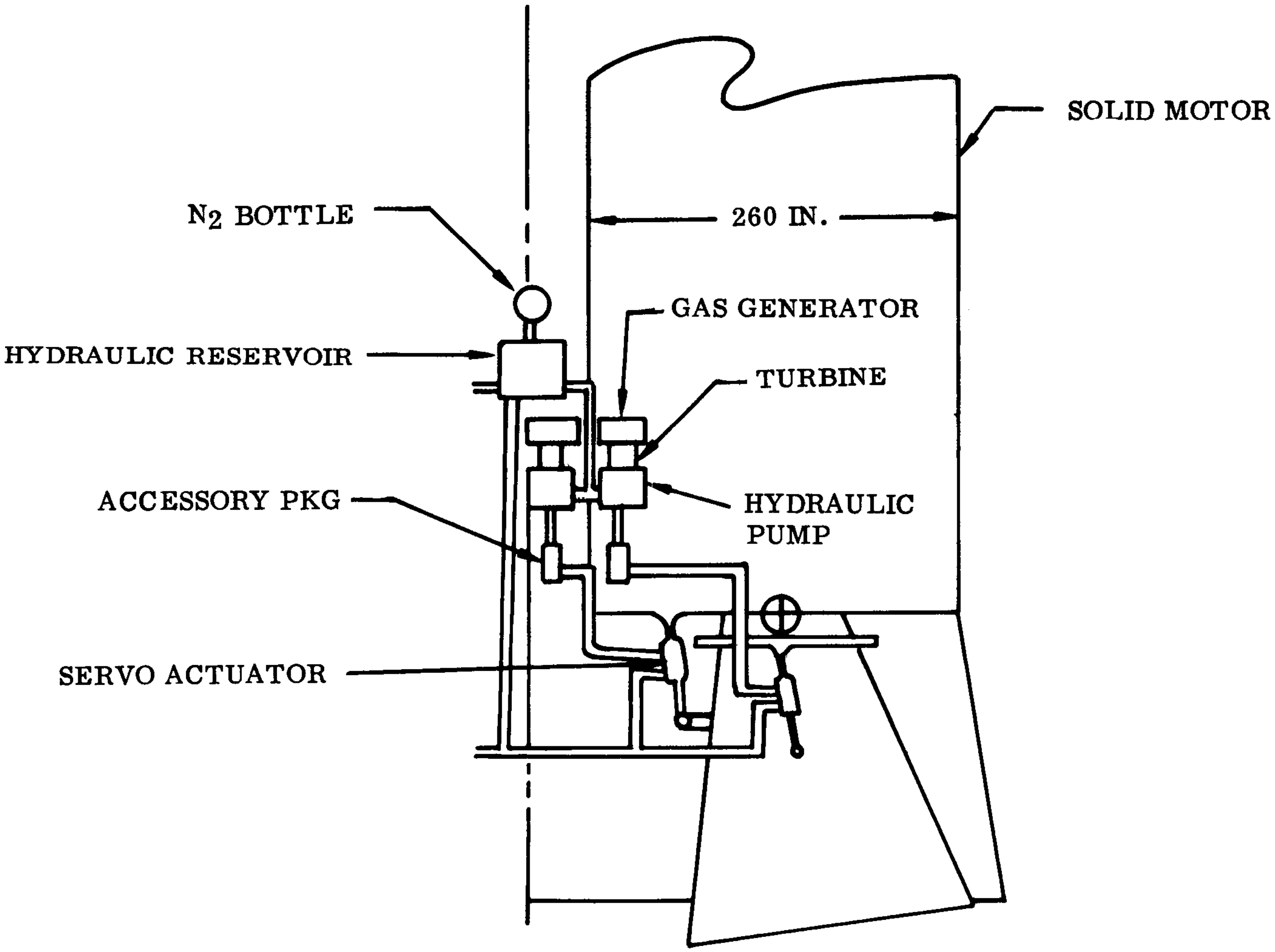
The complexity and relative sizes of TVC components are shown for a gimbaled-nozzle recirculating-fluid system.

The actuation system pictured with the gimbaled nozzle requires an individual power source for each servoactuator because of size. Each power source is a slow-burning solid-propellant gas generator, gas turbine, power package, and hydraulic pump. A common hydraulic reservoir is used for all servoactuators. Nitrogen pressurization supplies the suction head to the pumps. Used fluid is recirculated to the reservoir. Although individual power sources are required to satisfy maximum vehicle response requirements, reliability is increased since partial control may be maintained if one is lost during flight.

GIMBALED NOZZLE

Recirculating Fluid

(500K Vehicle)



"VECTROL" SYSTEM

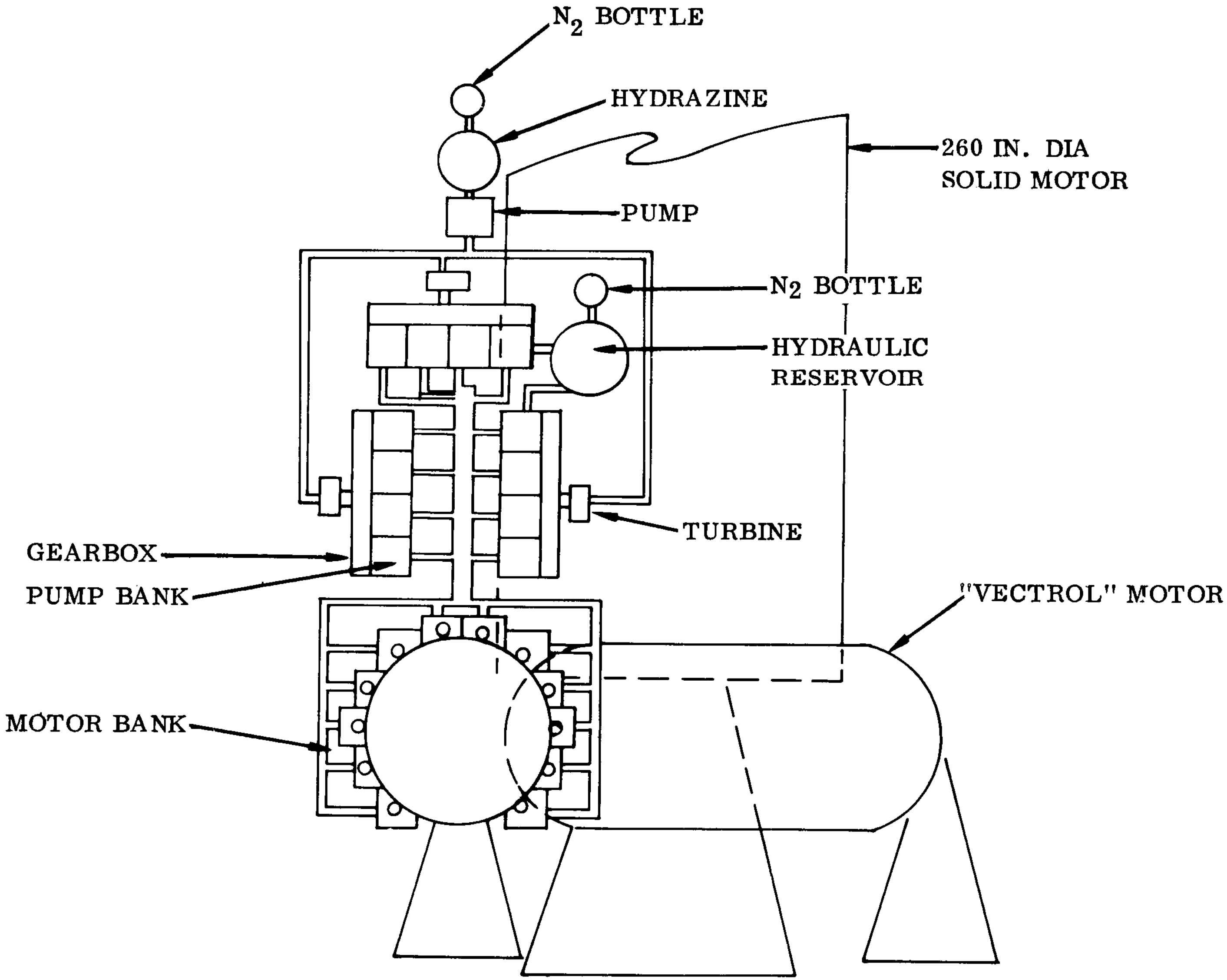
The complexity and relative sizes of TVC components are shown for a "Vectrol" solid auxiliary-motor system. Use of an auxiliary motor system allows the main thrust nozzles to be fixed and aligned parallel to the vehicle centerline.

Although the "Vectrol" rotatable motor is not complex, the system required to rotate it is highly complex. To satisfy maximum rotational requirements, 12 hydraulic pumps and motors of one of the largest industrial sizes available are required for each of the four "Vectrol" motors. Minimum vehicle requirements may be maintained during flight by only eight pumps and motors. Monopropellant hydrazine was chosen to power the turbine because the size requirements for a slow-burning solid-propellant gas generator were beyond adaptability to the vehicle configuration. The nitrogen pressurization supplies suction head to the pumps.

[redacted]

"VECTROL" MOTOR

500K Vehicle — W/O Fins



[redacted]

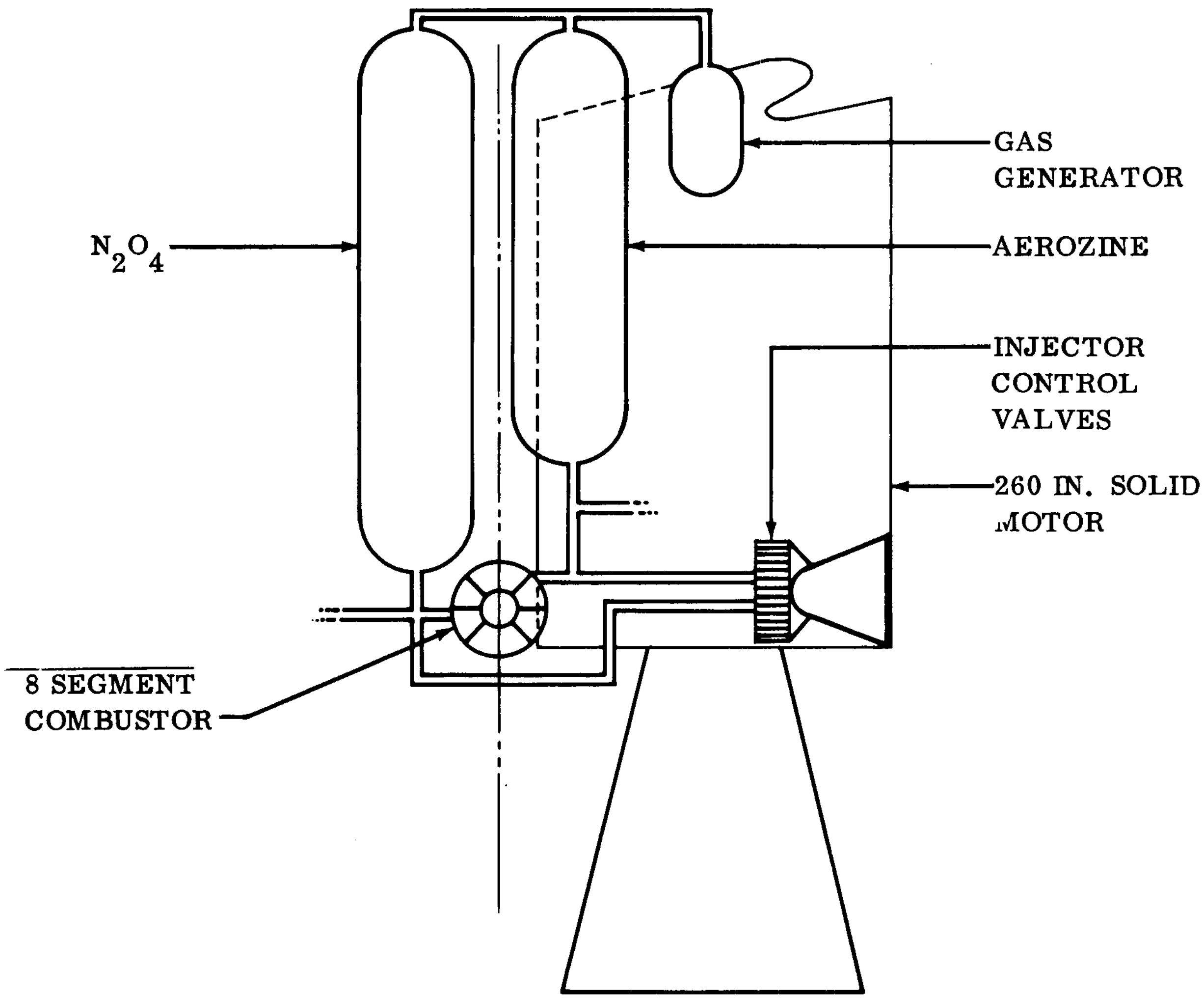
REACTION ENGINE — BIPROPELLANT

The complexity and relative sizes of TVC components are shown for a bipropellant liquid auxiliary engine system. Use of an auxiliary engine system allows the main thrust nozzles to be fixed and aligned parallel to the vehicle centerline.

The bipropellant, fixed-mounted reaction engines are of the eight-segment expansion-deflection type. The segments are operated individually in an on-off manner to provide variable thrust control. Pressurization is provided by a slow burning solid-propellant gas generator. Fuel and oxidizer tanks are common to the four reaction engines.

REACTION ENGINE
Bipropellant

(500K Vehicle)



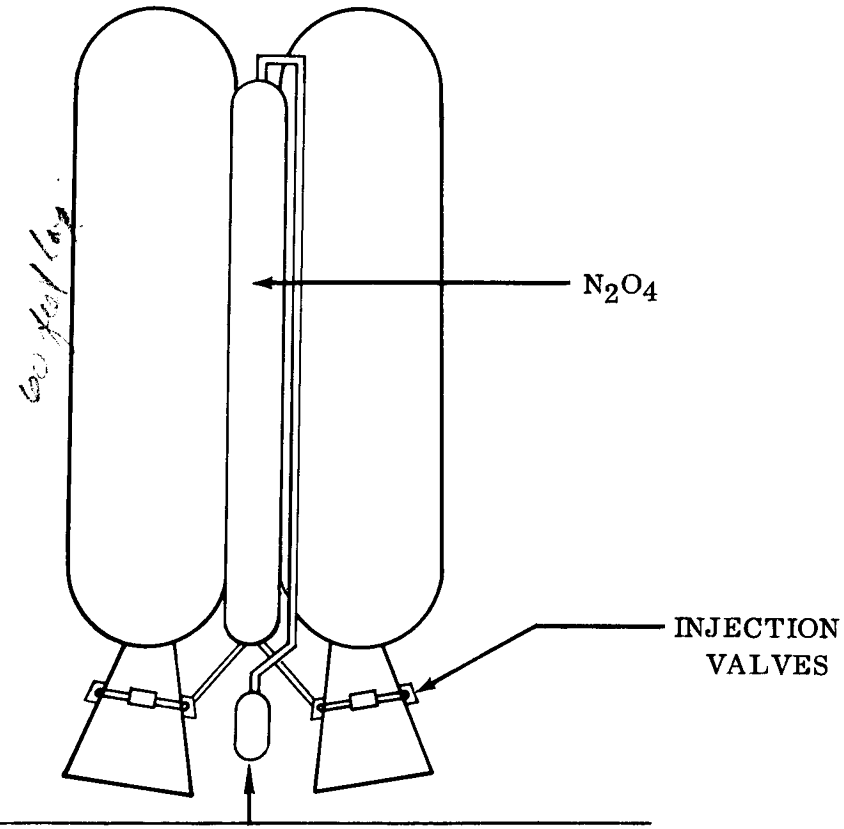
FLUID INJECTION — N_2O_4

The complexity and relative size of TVC components are shown for an N_2O_4 fluid injection system. The required injectant tank is extremely large but is adaptable to the vehicle by placing it in the center of the cluster structure. A survey of pressurization systems indicates that, compared to a cold gas system, the slow-burning solid-propellant gas generator is best from the standpoints of weight and development time.

FLUID INJECTION

N_2O_4

(500K Vehicle)



SOLID PROPELLANT GAS GENERATOR - 7500 LB

N_2 PRESSURIZATION - 38000 LB

PRELIMINARY TVC SYSTEM RATING

Ten thrust vector systems, representing four system categories, are compared by merit rating them against eight trade parameters. These parameters, selected from a total of 18 considered, are judged to show the greatest difference between systems. While a simple merit ranking of "poor," "good," and "best" indicates a system's relative worth, a more technical method is being developed.

Each of the four categories was reviewed to select representative systems warranting further study. The system in Category I to be analyzed in further detail, is the closed-loop hydraulic system for gimbaled nozzle thrust vector control. Categories II and IV show no systems warranting further analysis. The system chosen in Category III is the N_2O_4 injection system since the availability of N_2O_4 is better than, and its price somewhat less than, that of Freon.

To summarize, two systems were selected for the 500K vehicle; both now seem also best for the smaller vehicle. These are the 4000 psi closed-loop gimbaled nozzle system and the N_2O_4 injection system.

PRELIMINARY TVC SYSTEM RATING

500K Vehicle

TRADE PARAMETER	CATEGORY I				CATEGORY II		CATEGORY III			CAT. IV
	Hinged Nozzle (C.L.)	Hinged Nozzle (O.L.)	Gimbaled Nozzle (C.L.)	Gimbaled Nozzle (O.L.)	Aux. Motor N_2O_4 (50-50)	Aux. Motor "Vectrol"	Injection N_2O_4	Injection Freon 113	Injection N_2O_4 (50-50)	Combination
DEVELOPMENT STATUS	Best	Good	Good	Poor	Poor	Poor	Good	Good	Poor	Poor
RELIABILITY	Good	Good	Good	Good	Good	Best	Best	Best	Good	Poor
COST	Best	Best	Good	Good	Poor	Poor	Good	Good	Good	Poor
GROWTH	Best	Best	Best	Best	Poor	Poor	Good	Good	Good	Poor
VEHICLE ADAPTABILITY	Best	Best	Best	Best	Good	Poor	Good	Good	Good	Good
STAGING CONTROL	Poor	Poor	Good	Good	Best	Best	Good	Good	Good	Good
CONTROL WITH ONE TVC SYSTEM OUT	Poor	Poor	Best	Good	Poor	Good	Good	Good	Poor	Poor
EQUIVALENT WEIGHT	BEST	BEST	GOOD	GOOD	BEST	POOR	POOR	POOR	GOOD	GOOD

BLANK

CLUSTER STRUCTURE

J.A. Dellworth

VEHICLE SUPPORT CONCEPTS

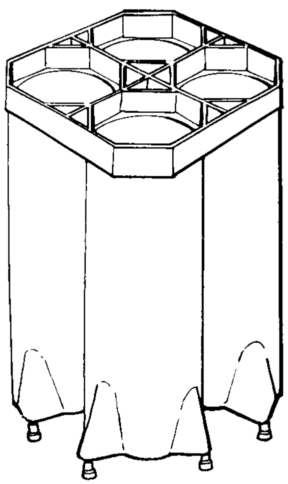
To briefly review, the total program includes three basic methods of supporting the vehicle on the launch stand. These methods are:

1) Supporting the vehicle on the skirt extension of the motor case,

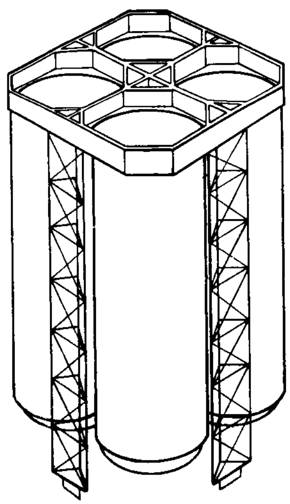
2) Supporting the vehicle on a framework that will carry the stand loads into the interstage structure — this framework, called the space frame, flies with the missile,

3) Supporting the vehicle at the interstage by means of towers — these towers do not fly with the vehicle.

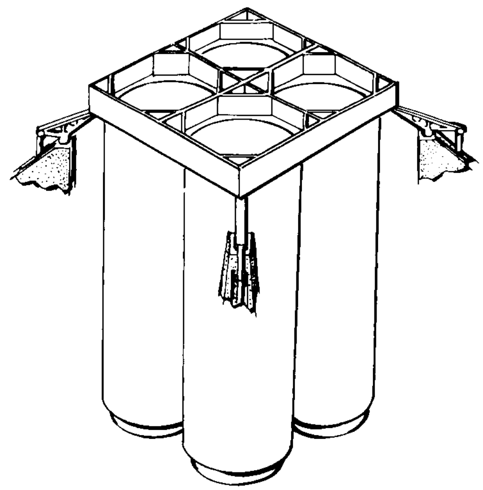
VEHICLE SUPPORT CONCEPTS



SKIRT



SPACE FRAME



TOWER
SUPPORT
(TYP 4
PLACES)

CLUSTER CONCEPTS

The cluster concepts assumed for the study are shown in this chart. They are:

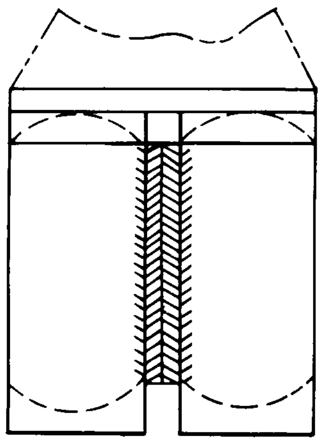
1) A continuous shear tie between the adjacent motor cases;

2) The motor cases cantilevered from a barrel section at the forward end;

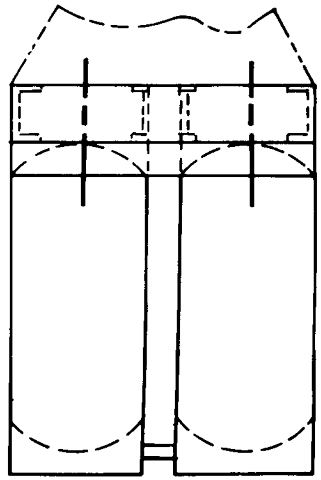
3) The motor cases cantilevered from the forward end by attaching them to a structure formed by a crossbeam between the motor cases and a band running around the outside of the cases;

4) An attachment at both ends.

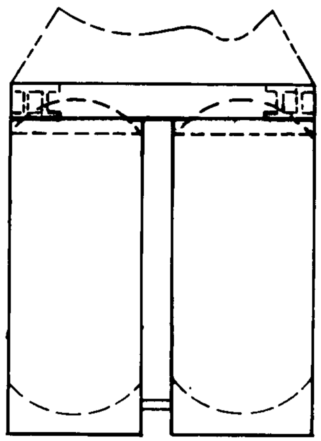
CLUSTER CONCEPTS



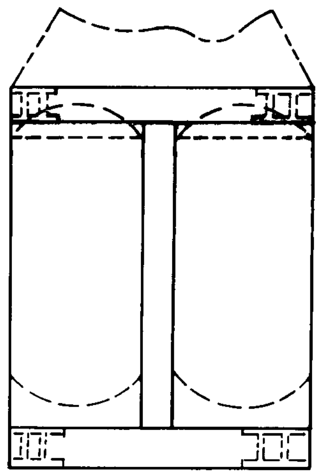
SHEAR TIE



BARREL TIE



CROSS BEAM



TWO-END TIE

ESTIMATED STRUCTURAL WEIGHTS

The structural weights presented represent the best weight estimate available for each concept at this time. These values are subject to modification upon completion of the COSMOS analysis. It must be emphasized that second-order effects may be important in the final selection of a clustering concept. Excessive deflections in a critical area could make a particular concept undesirable regardless of its weight-saving capabilities.

ESTIMATED STRUCTURAL WEIGHT (LBS.)

500K VEHICLE

	ONE-END TIE CONCEPTS					
	BARREL	CROSS BEAM	SHEAR TIE	TWO-END TIE	SPACE FRAME	INTERSTAGE SUPPORT
FORWARD INTERSTAGE	18,000	18,000	18,000	18,000	18,000	18,000
CLUSTERING STRUCTURE	115,000	70,000	60,000	85,000	135,000	100,000
AFT SKIRT	20,000	20,000	20,000	20,000	10,000	10,000
TOTALS	153,000	108,000	98,000	123,000	163,000	128,000

STRUCTURAL DEFLECTIONS

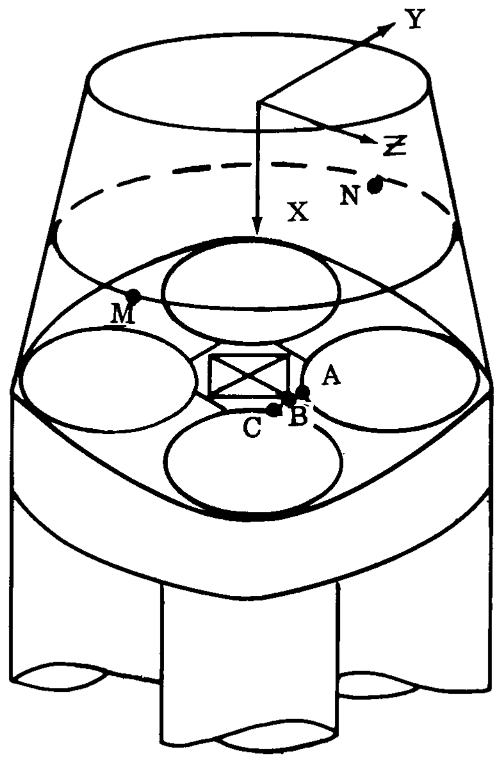
Typical deflections calculated by the COSMOS analysis program are shown. The deflections at points A, B, and C are for the condition of one engine out at burnout. (A′, B′, and C′ are the corresponding points in the plane at the bottom of the barrel sections.) These deflections indicate excessive relative displacement of the tanks in the longitudinal direction. One corrective measure would be to increase the size of member ABC. However, a more realistic solution might be to join points A-A′-C′-C with a shear tie.

The displacements at Points M and N are for the burnout condition. They illustrate the bulging effect at the middle of the interstage for maximum axial load. These deflections may at first appear large. However, when compared to the size of the structure involved, they are not unreasonable.

STRUCTURAL DEFLECTIONS

Investigation of Second-Order Effects

POINT	DEFLECTION
A	X = -4.34"
B	X = -2.67"
C	X = -.77"
A'	X = -4.41"
B'	X = 2.66"
C'	X = -.75"
M	Y = -5.40"
N	Y = +5.40"



CONCENTRATED CASE-LOAD STUDY

The clustering of large boosters may induce concentrated loads in the motor cases. The purpose of this study is to review and define such problems and to present methods for their solution.

CONCENTRATED CASE-LOAD STUDY

Problem = [High Bi-Axial Membrane Stresses] + [Brittle Failures (Little Local Yielding)] + [Local Stress Peaks Due to Clustering, etc.] = [Weight And Cost Penalties]

Problem Causes = [Joint Compatibility Requirements] + [Concentrated Load Redistributions] + [Pressurization Constraints]

Study Objectives = [Define Maximum Local Stress Increases] + [Present Data In Generalized Charts Suitable For Preliminary Design]

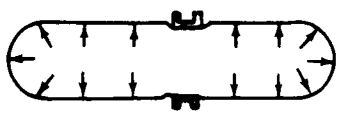
Study Results = [Head-To-Cylinder Joint Discontinuity Stresses] + [Pressurized Case With Local Ring Restraints] + [Pressurized Case With Local Longtudinal Restraints] + [Stresses Due to Concentrated Radial Loads] + [Stresses Due to Concentrated End-Load Shear Lag Action]

TYPICAL CASE-LOAD CONCENTRATIONS

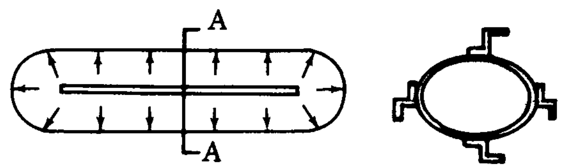
Local stress increases may arise due to compatibility requirements, pressure constraints, or concentrated loadings. Some typical examples are shown.

TYPICAL CASE-LOAD CONCENTRATIONS

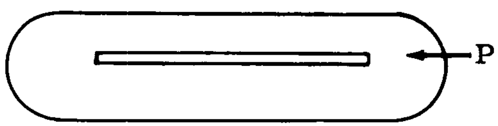
Radial Constraint



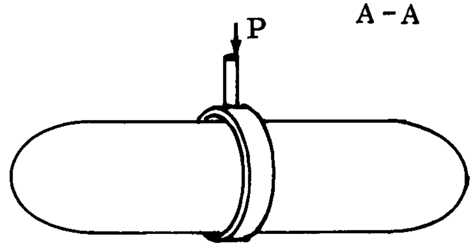
Axial Constraint



Pressurization Constraints

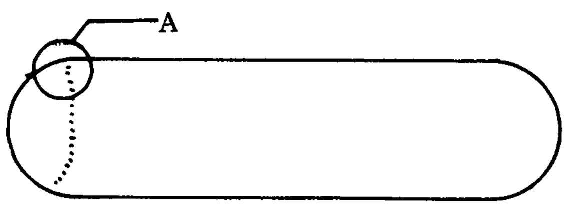


Axial Load Concentrations

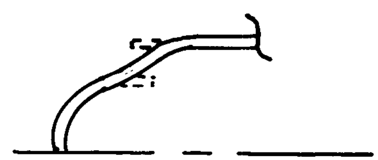


Radial Load Concentration

Redistribution of Concentrated Loads



Typical Pressurized Cylinder



Joint Detail "A"

Joint Compatibility Requirements

TYPICAL CASE DESCRIPTION

For all loading conditions, the basic data equations, nomenclature, and a sketch are included. Typical descriptive information is shown.

Nomenclature

P = Internal case pressure

R = Case radius

E = Elastic modules of case material

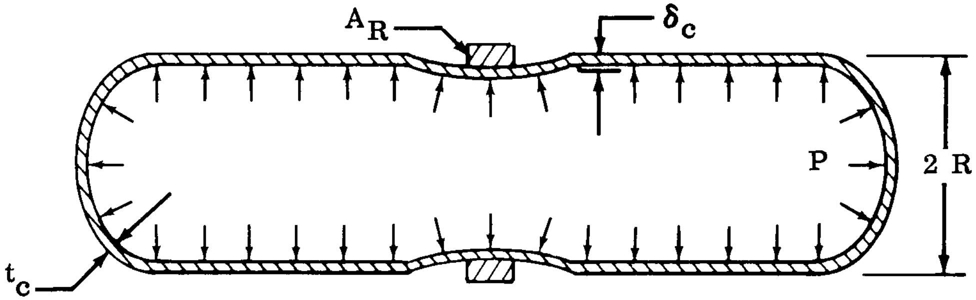
E_R = Elastic modules of ring material

t_c = Case wall gage

A_R = Ring cross-sectional area

μ = Poissons ratio of case material

TYPICAL CASE DESCRIPTION



$$\frac{\Delta \sigma_{\phi c}}{\left(\frac{PR}{t_c}\right)} = \frac{1.5\left(1 - \frac{\mu}{2}\right)\left(\frac{A_R}{t_c\sqrt{R\,t_c}}\right)\left(\frac{E_R}{E}\right)}{\sqrt[4]{3\,(1-\mu^2)}\left[1 + \frac{\sqrt[2]{3\,(1-\mu^2)}}{2}\left(\frac{A_R}{t_c\sqrt{R\,t_c}}\right)\left(\frac{E_R}{E}\right)\right]}$$

$$\frac{\Delta \sigma_{\theta c}}{\left(\frac{PR}{t_c}\right)} = \frac{\left[\frac{1.5\left(1 - \frac{\mu}{2}\right)\mu}{\sqrt[4]{3\,(1-\mu^2)}} - \frac{\left(1 - \frac{\mu}{2}\right)\sqrt[4]{3\,(1-\mu^2)}}{2}\right]\left(\frac{A_R}{t_c\sqrt{R\,t_c}}\right)\left(\frac{E_R}{E}\right)}{\left[1 + \frac{\sqrt[4]{3\,(1-\mu^2)}}{2}\left(\frac{A_R}{t_c\sqrt{R\,t_c}}\right)\left(\frac{E_R}{E}\right)\right]}$$

$$\frac{\delta_c}{\left(\frac{PR^2}{E\,t_c}\right)} = \frac{\left(1 - \frac{\mu}{2}\sqrt[4]{3\,(1-\mu^2)}\left(\frac{A_R}{t_c\sqrt{R\,t_c}}\right)\left(\frac{E_R}{E}\right)\right)}{1 + \sqrt[4]{3\,(1-\mu^2)}\left(\frac{A_R}{t_c\sqrt{R\,t_c}}\right)\left(\frac{E_R}{E}\right)}$$

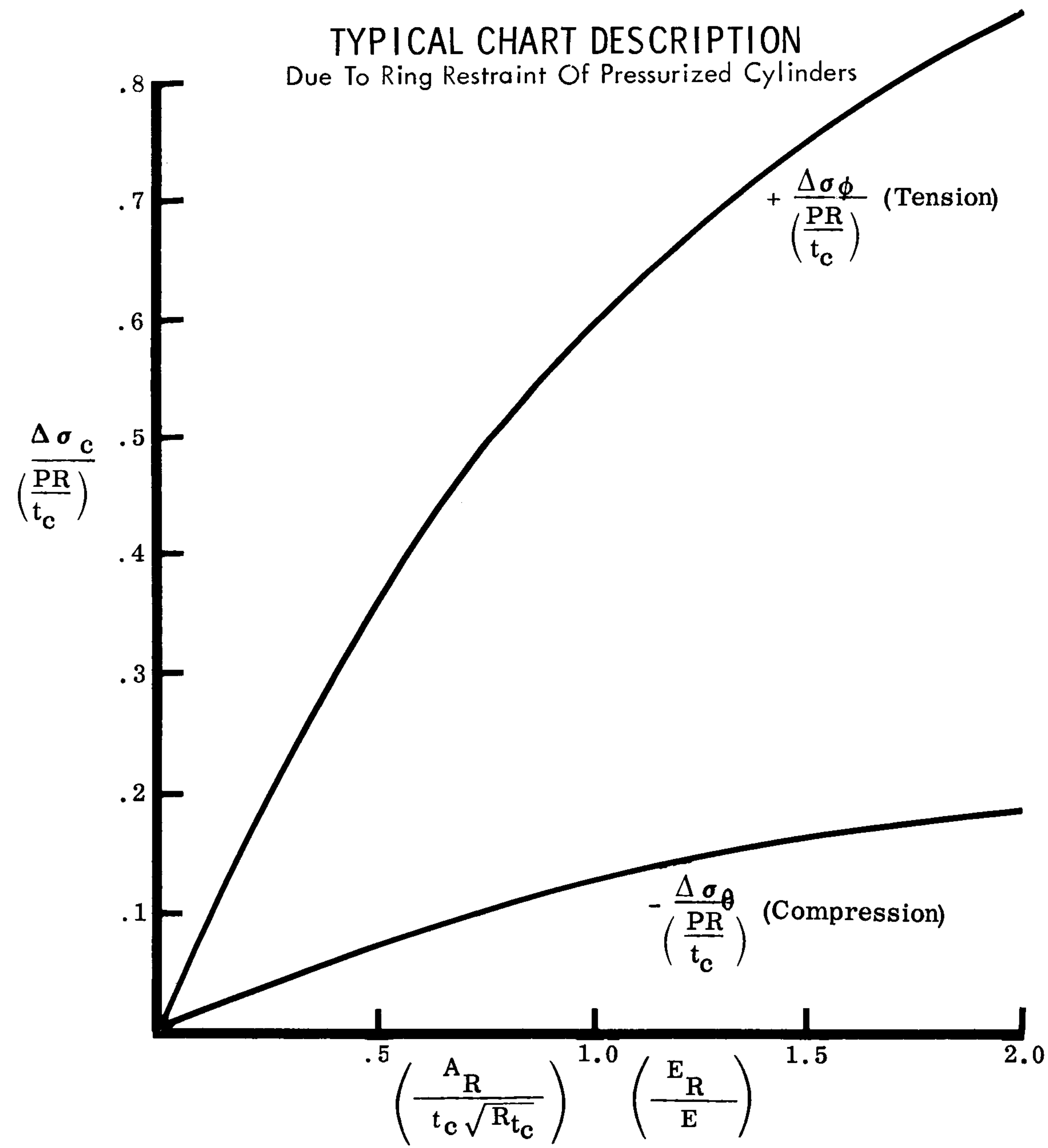
$\Delta \sigma_\theta$ = Maximum hoop stress increment.

$\Delta \sigma_\phi$ = Maximum longitudinal stress increment.

δ_c = Local case deformation due to ring restraint.

TYPICAL CHART DESCRIPTION

The results of this study are presented in a form suitable for preliminary design use. In general, these charts show the stress increases due to load concentrations in terms of basic geometric and material properties. A typical chart is shown.


TYPICAL CHART DESCRIPTION
Due To Ring Restraint Of Pressurized Cylinders
.8
.7
.6
.5
.4
.3
.2
.1
$\frac{\Delta \sigma_c}{\left(\frac{PR}{t_c}\right)}$
$+\frac{\Delta \sigma_\phi}{\left(\frac{PR}{t_c}\right)}$ (Tension)
$-\frac{\Delta \sigma_\theta}{\left(\frac{PR}{t_c}\right)}$ (Compression)
.5
1.0
1.5
2.0
$\left(\frac{A_R}{t_c \sqrt{R t_c}}\right) \left(\frac{E_R}{E}\right)$

SAMPLE PROBLEM

To show the recommended procedure, a sample problem will be solved for a simple case. The data is shown on the opposite page.

SAMPLE PROBLEM

GIVEN: A Steel Motor Case of 130-inch Radius and 0.75-inch Thickness Based on Membrane Loading Requirements

PROBLEM: (a) If the Case is to be Encircled by an Aluminum Redistribution Ring, What are the Maximum Induced Stresses in the Case?

(b) How Much Thickness Must be Added to Accommodate the Additional Stresses, if the Case Material Has a 200,000 PSI Ultimate Strength?

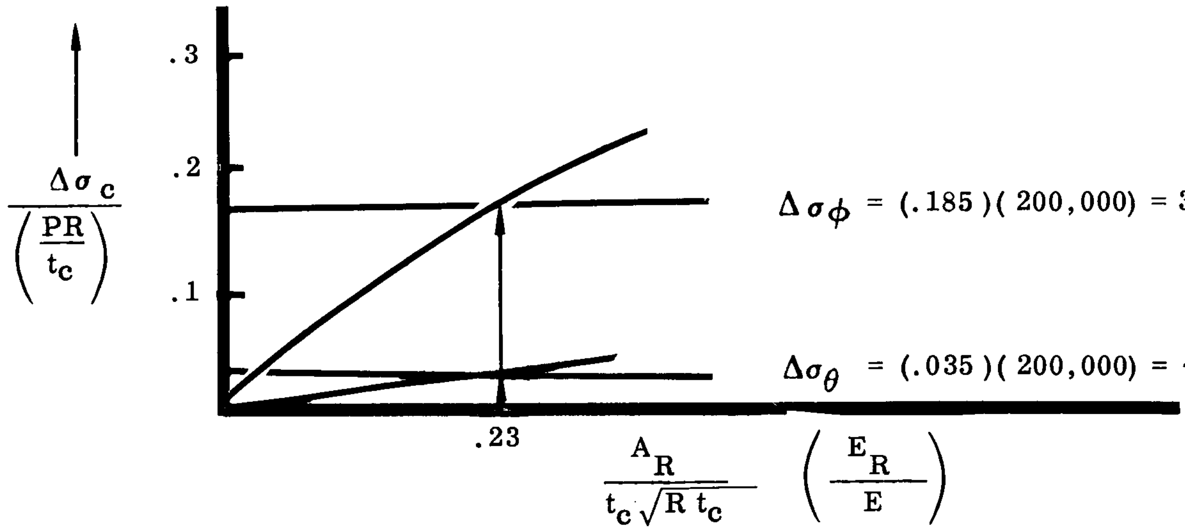
ASSUME: Ring Cross-Sectional Area = 5 square inches.

SAMPLE PROBLEM SOLUTION

The manner in which the charts may be used to obtain problem solutions is indicated on opposite page.

SAMPLE PROBLEM SOLUTION

$$\frac{A_R}{t_c\sqrt{Rt_c}}\left(\frac{E_R}{E}\right) = \frac{(.5)}{.75\sqrt{(130)(.75)}}\left(\frac{10.3 \times 10^6}{30 \times 10^6}\right) = \underline{.23}$$



$\Delta\sigma_\phi$ = (.185)(200,000) = 37,000 PSI

$\Delta\sigma_\theta$ = (.035)(200,000) = -7000 PSI

The Resulting Maximum Design Stresses Are:

σ_θ = 200,000 - 7000 = 193,000 PSI
σ_ϕ = 100,000 + 37,000 = 137,000 PSI

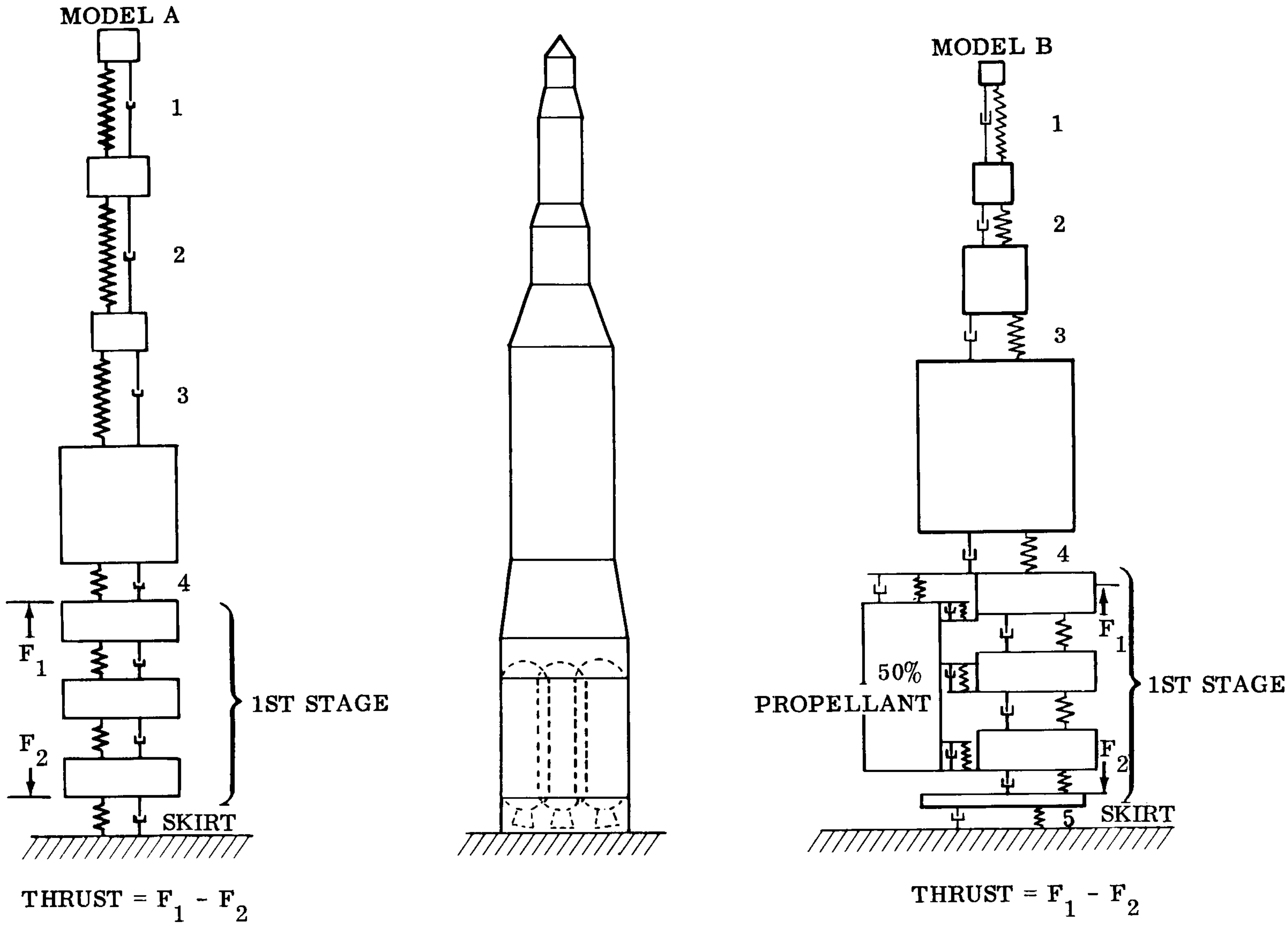
Since the Case is Good for 200,000 PSI, no Gage Increase is Necessary

DYNAMIC MODEL SKIRT SUPPORT — 500K VEHICLE

The two dynamic models that were used to represent the 500K configuration with skirt support for the symmetrical ignition transient study are shown. Model A treats the propellant as acting integrally with the case structure. Model B, similar to the Minuteman dynamic model, treats 50 percent of the propellant as acting with the case through shear springs and the remaining 50 percent acting directly with the case structure.

DYNAMIC MODEL

Skirt Support — 500K Vehicle



SKIRT STIFFNESS EFFECTS

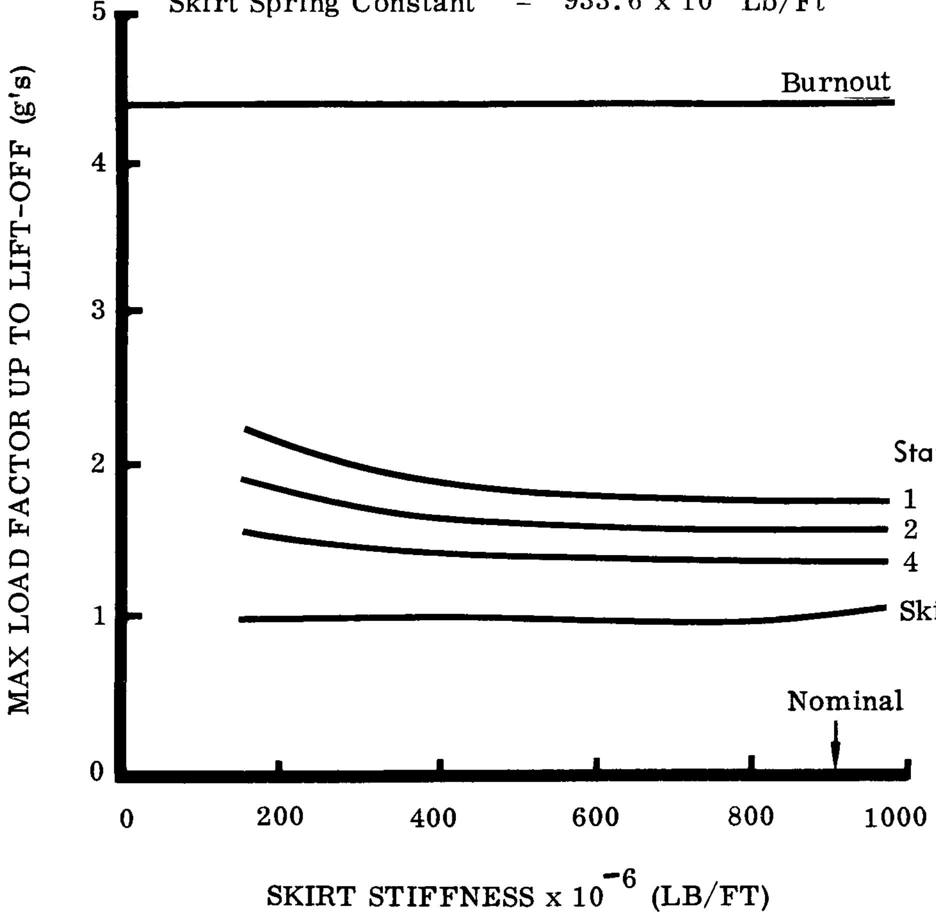
The effect of skirt stiffness on maximum load factors along the vehicle up to the time of vehicle liftoff is shown, using both Models A and B. The results of both models indicate an increase in load factors for Stations 1 through 4 for the lower values of skirt stiffness. The lower skirt stiffness values result in larger displacement of the 1st stage during unloading of the skirt. This in turn results in greater relative motion of the upper stations and causes higher load factors.

The skirt load factor increases very slightly with higher skirt stiffness for both Models A and B. Although the magnitudes of the load factors differ somewhat for the two models, the trends in the load factors vs. stiffness are essentially the same. Also, the load factors for Stations 1 through 4 are well below burnout load factors.

SKIRT STIFFNESS EFFECTS

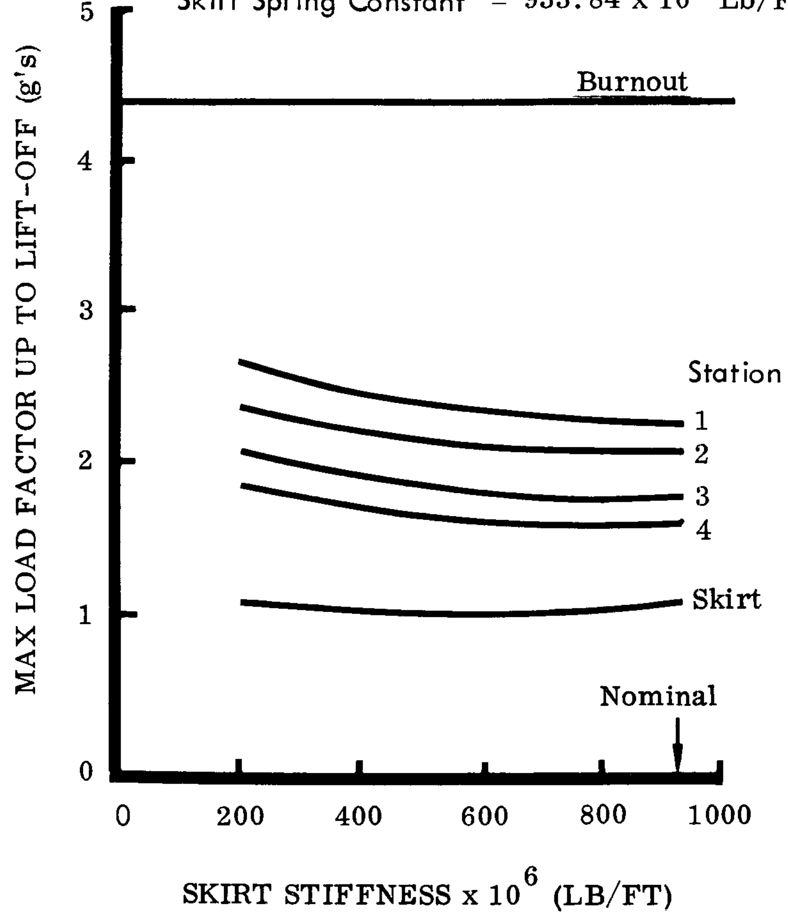
Skirt Support MODEL A
Symmetrical Loading

Thrust to Weight	=	1.5 g's
Rise Time	=	.3 Sec
Damping Ratio	=	.02 - .04
Skirt Spring Constant	=	933.6×10^6 Lb/Ft



Skirt Support MODEL B
Symmetrical Loading

Thrust to Weight	=	1.5 g's
Rise Time	=	.3 Sec
Damping Ratio	=	.02
Skirt Spring Constant	=	933.84×10^6 Lb/Ft

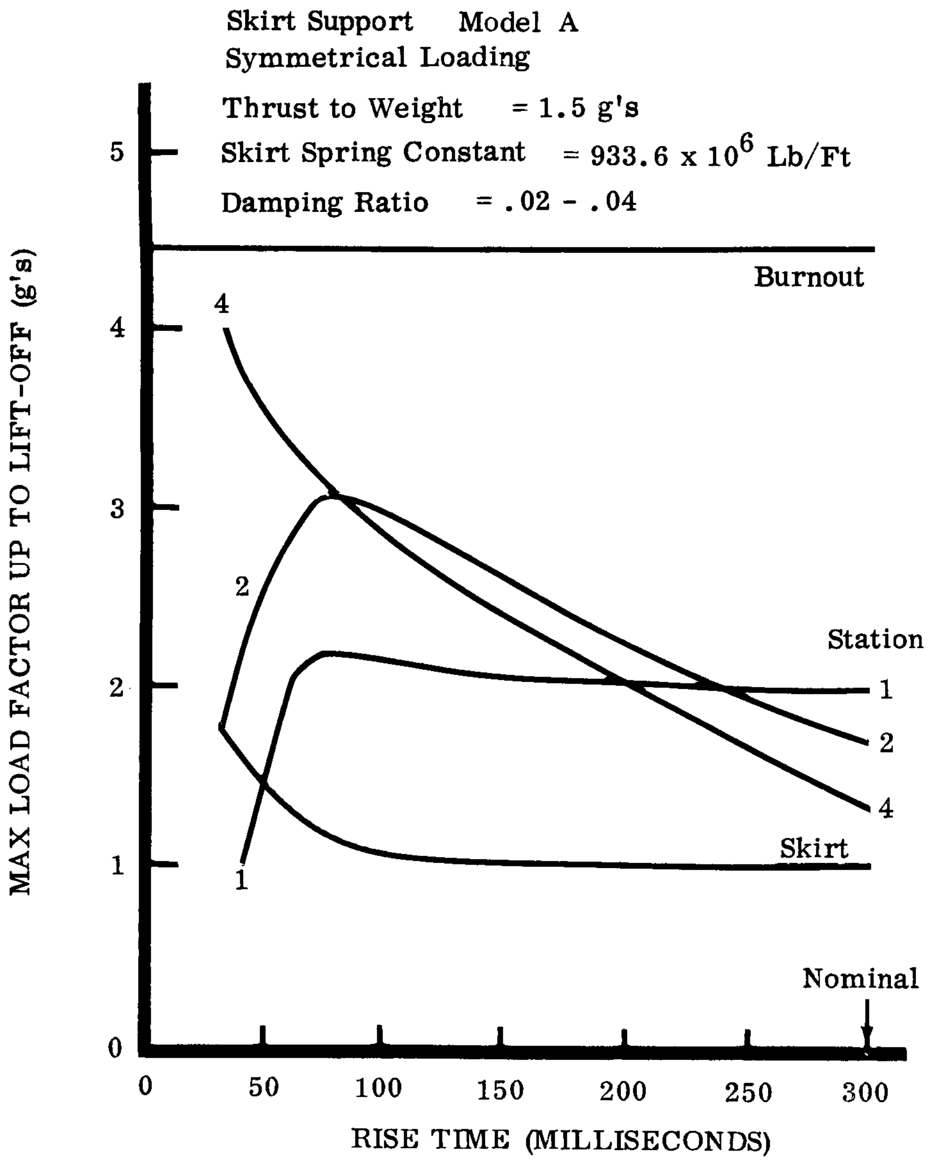


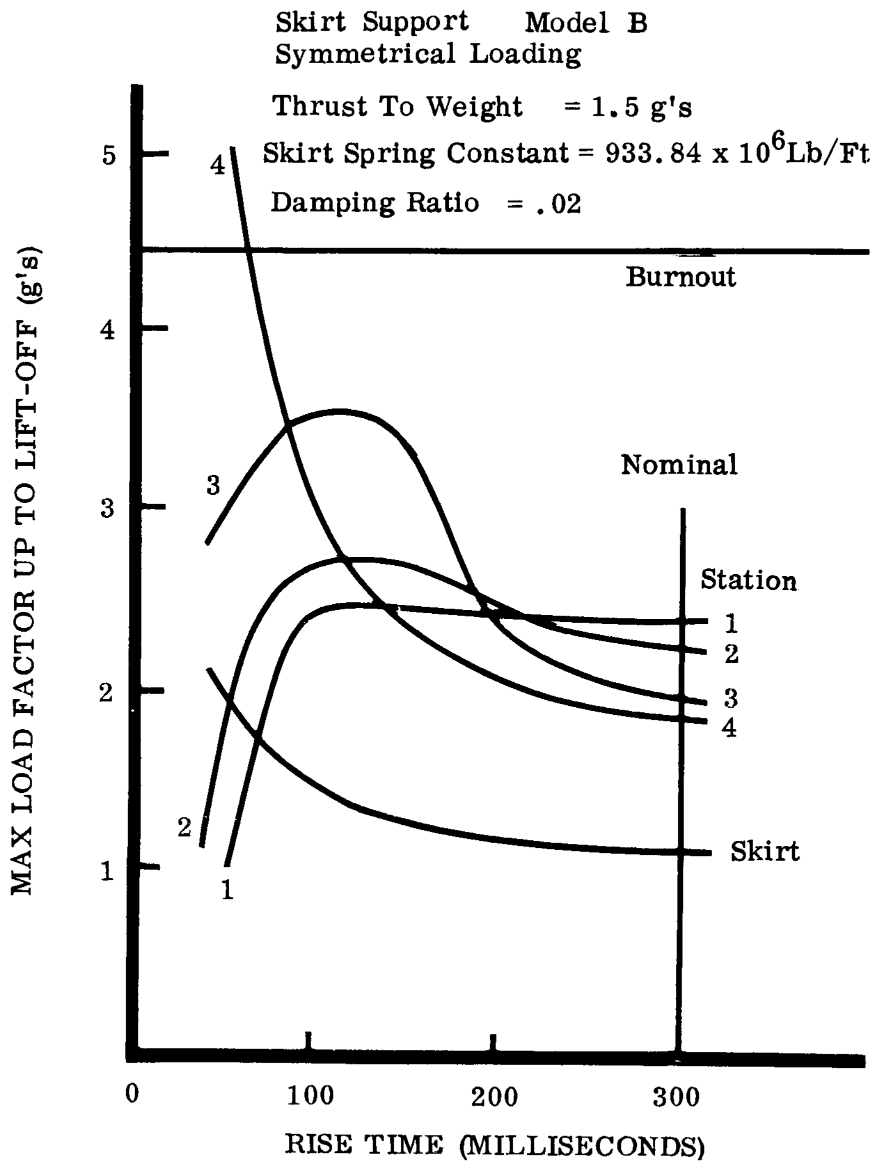
PRESSURE RISE TIME EFFECTS

The influence of pressure rise time on vehicle load factors up to liftoff are shown for both models. The results of both models indicate that for the upper stations the load factors get larger and then smaller as the rise time is reduced from the nominal. For the lower station and the skirt, the load factor continues to build up as the rise time is reduced from nominal. Again, although the magnitudes of the results for Models A and B differ somewhat, the trends shown by each model are similar.

The load factors at the nominal value of rise time are well below burnout load factors. Since the actual rise times are well above natural periods of the vehicle, large dynamic magnifications will not occur and, hence, load factors will remain much lower than burnout values.

PRESSURE RISE TIME EFFECTS





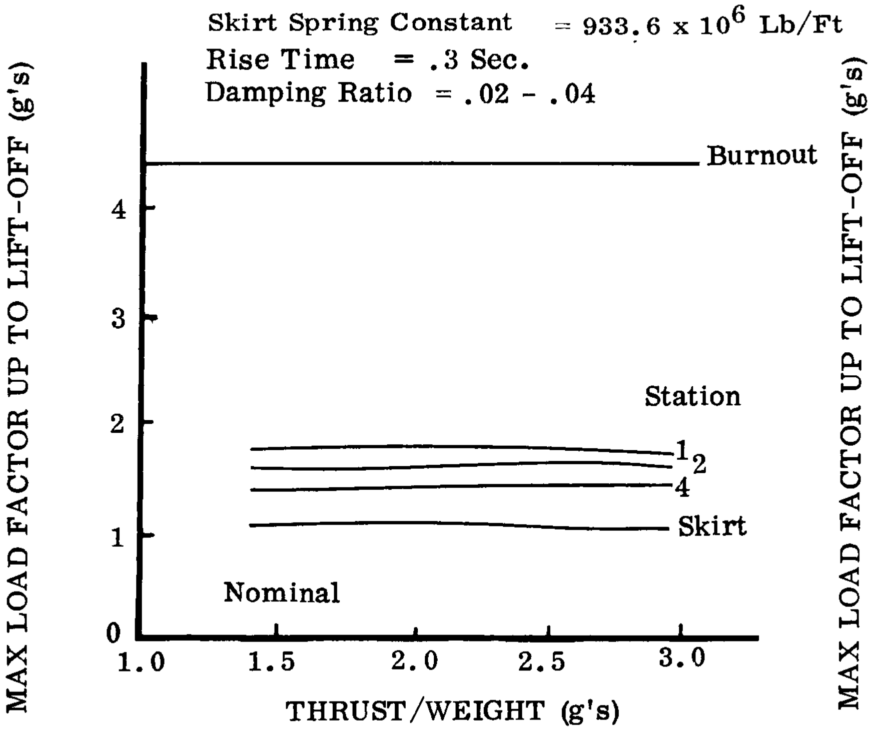
THRUST/WEIGHT EFFECTS

The results of Model A show little effect of thrust/weight change on vehicle load factors, while the results of Model B show that load factor increases with increasing thrust/weight. The difference in these trends resulted from the difference in the application of the forcing function on each model. That is, for Model A the thrust/weight increase was obtained by increasing the exit area while maintaining the same internal pressure time history. Model B exit area was held constant while the pressure time history values were increased.

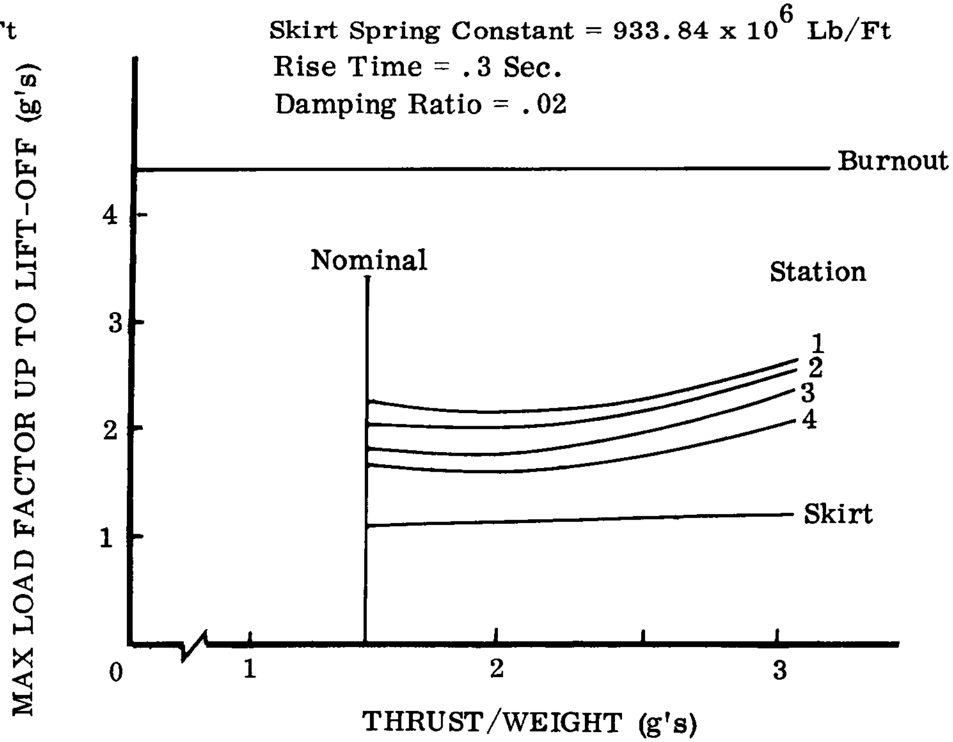
At the nominal value of thrust/weight, the load factors up to lift-off are much lower for both models than the burnout load factor.

THRUST / WEIGHT EFFECTS

Skirt Support MODEL A
Symmetrical Loading



Skirt Support MODEL B
Symmetrical Loading

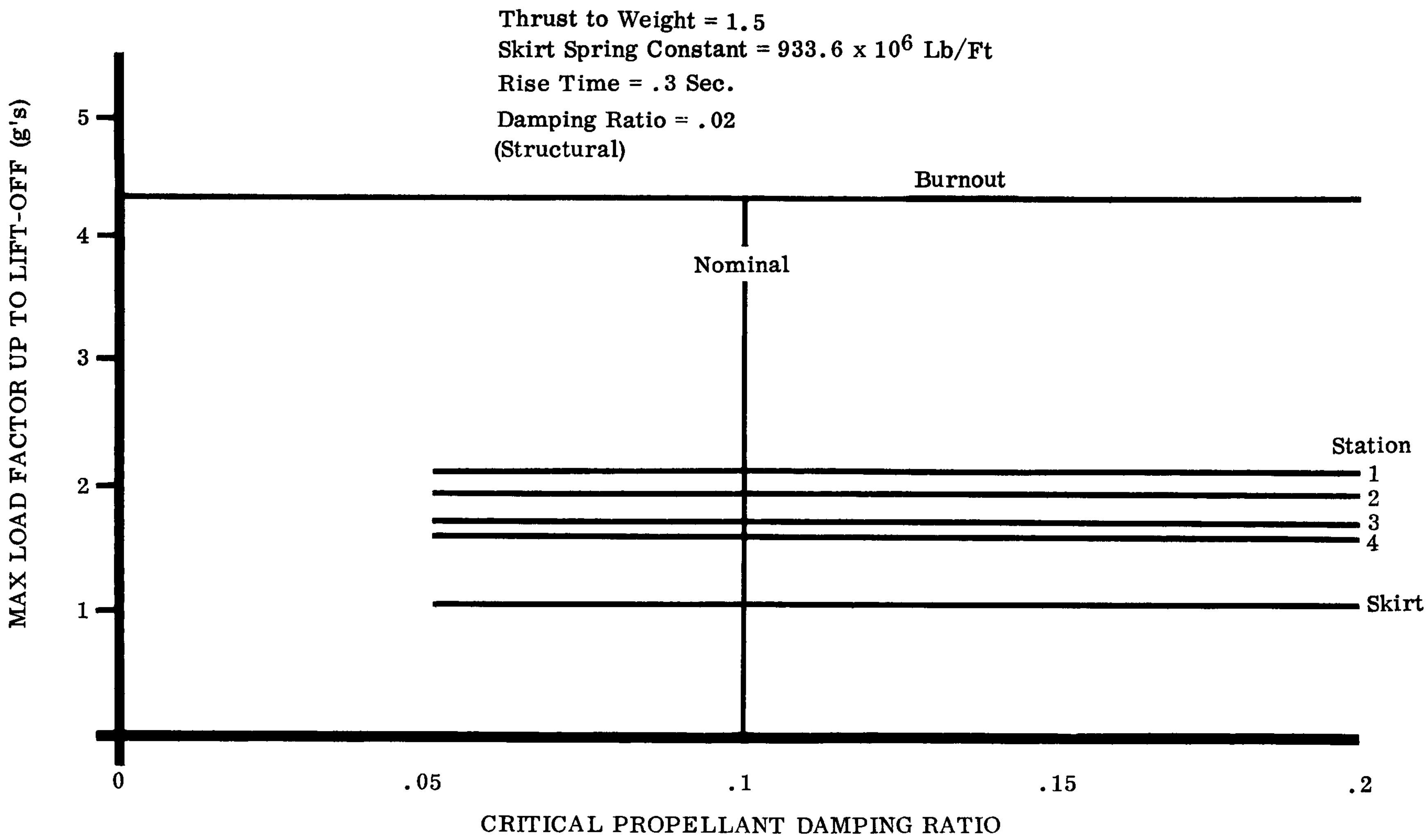


PROPELLANT DAMPING EFFECTS

A study of the effect of propellant damping ratio on vehicle load factors was carried out only on Model B. The results show that the load factors up to lift-off are unchanged by varying propellant damping ratio.

PROPELLANT DAMPING EFFECTS

Skirt Support Model B Symmetrical Loading



LOAD FACTOR VARIATIONS WITH TIME

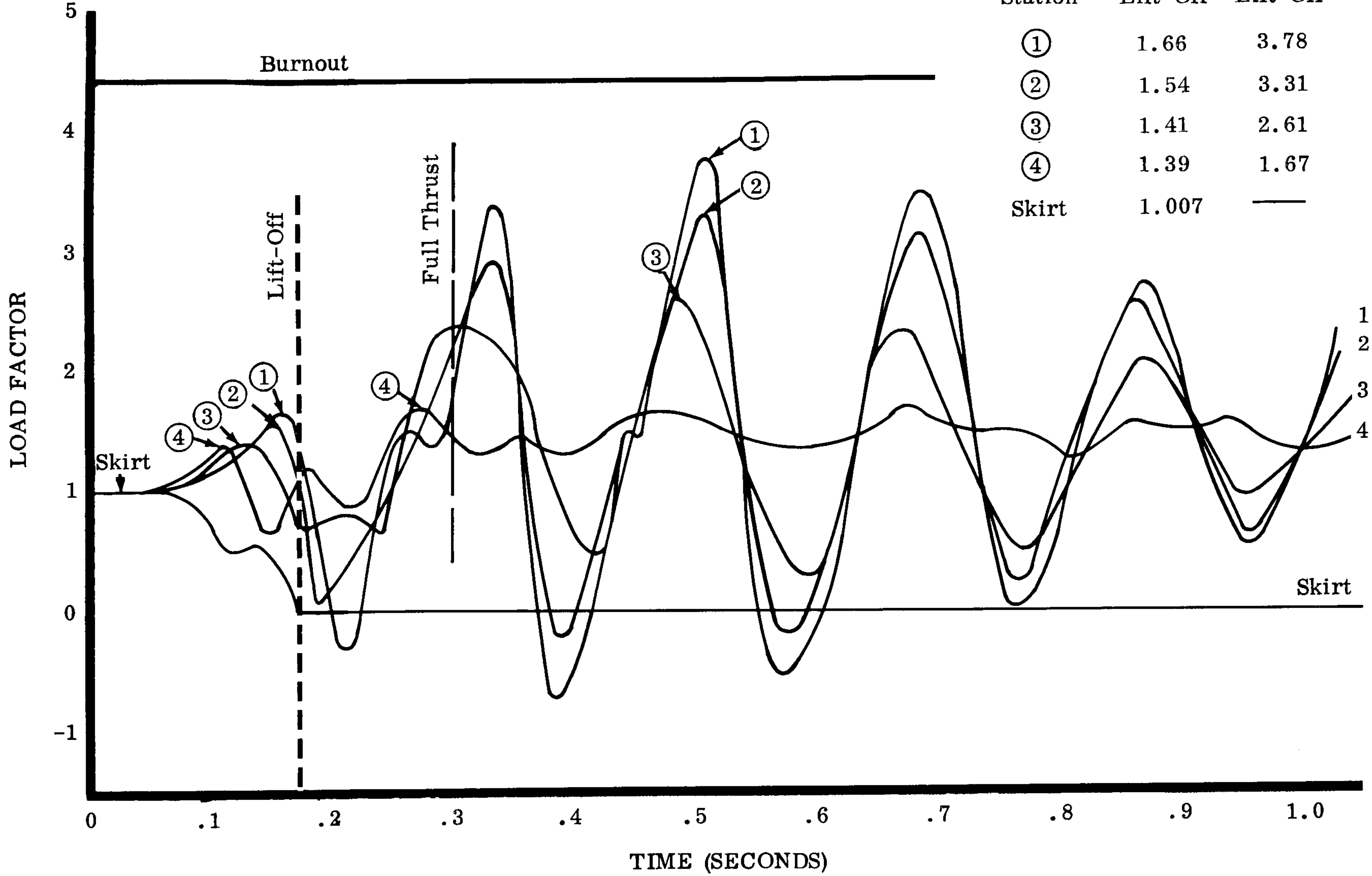
The time histories of the vehicle load factors up to and after lift-off for Model B (nominal case) are shown. The results indicate that the load factors for Stations 1 through 4 are considerably greater after lift-off than up to lift-off. This plot indicates that the largest load factors occur when the oscillations of the upper stations are in phase. The phase convergence takes place about 500 milliseconds after ignition and oscillations subsequently damp out.

The result indicates that certain parameter investigations should be extended beyond lift-off since the load factors after lift-off in the 3rd stage and the payload are approaching those of burnout and hence could constitute a design problem.

LOAD FACTOR VARIATIONS WITH TIME

MODEL B

Station	Max Load Factors Before Lift-Off	Max Load Factors After Lift-Off
1	1.66	3.78
2	1.54	3.31
3	1.41	2.61
4	1.39	1.67
Skirt	1.007	——



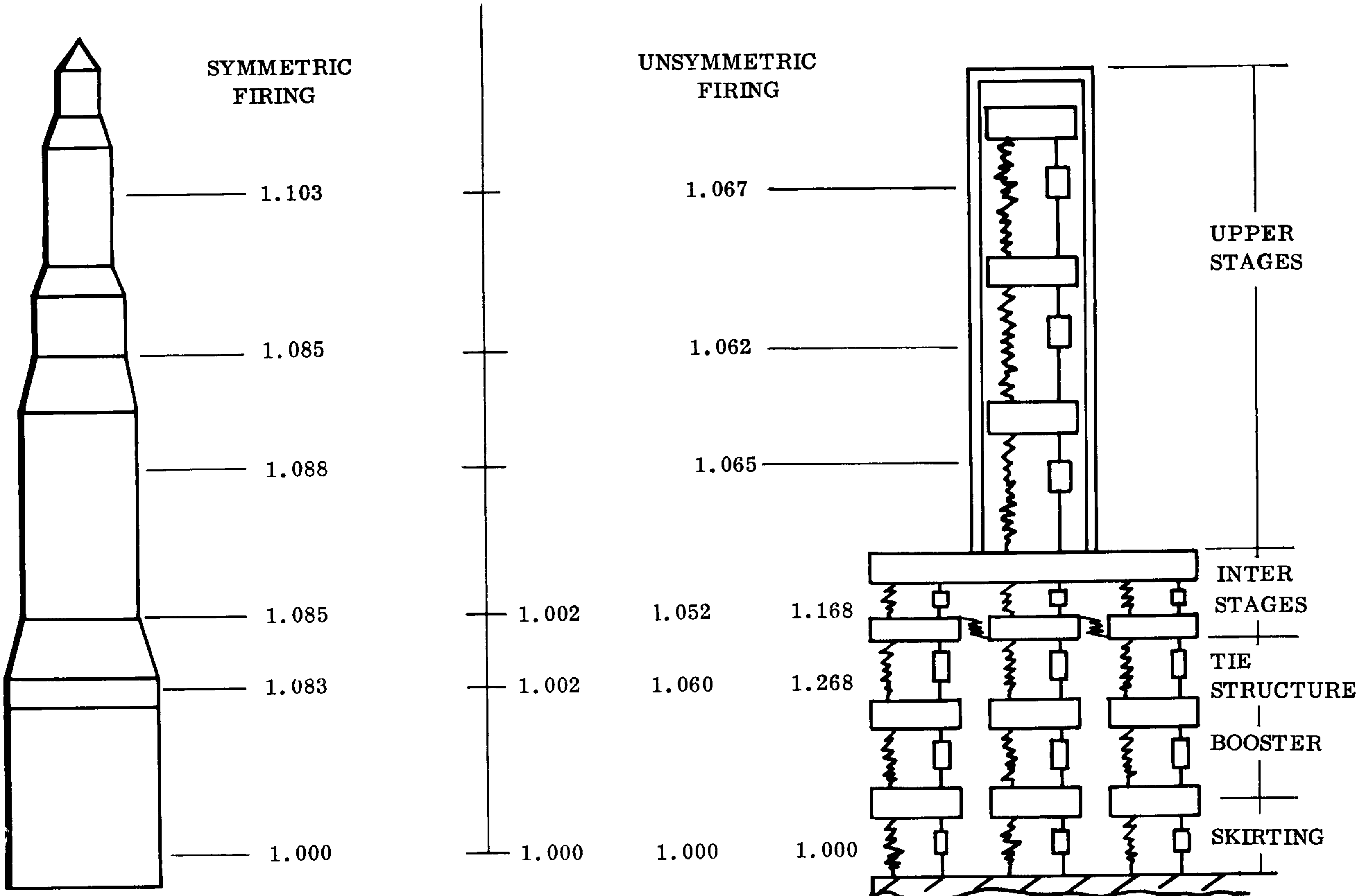
LOAD FACTOR COMPARISON

A comparison is shown between load factors obtained during symmetrical and unsymmetrical firings up to lift-off, the load factor being defined as the ratio of maximum loading to static 1-g load.

These results indicate that there is no appreciable difference between the load factors obtained during symmetrical and unsymmetrical firings.

Further results indicated that rotation of the vehicle during unsymmetrical firing is about .001 degree. This value was obtained at lift-off.

LOAD FACTOR COMPARISON



These Are Load Factors Up To Liftoff

DYNAMIC MODEL — SPACE FRAME

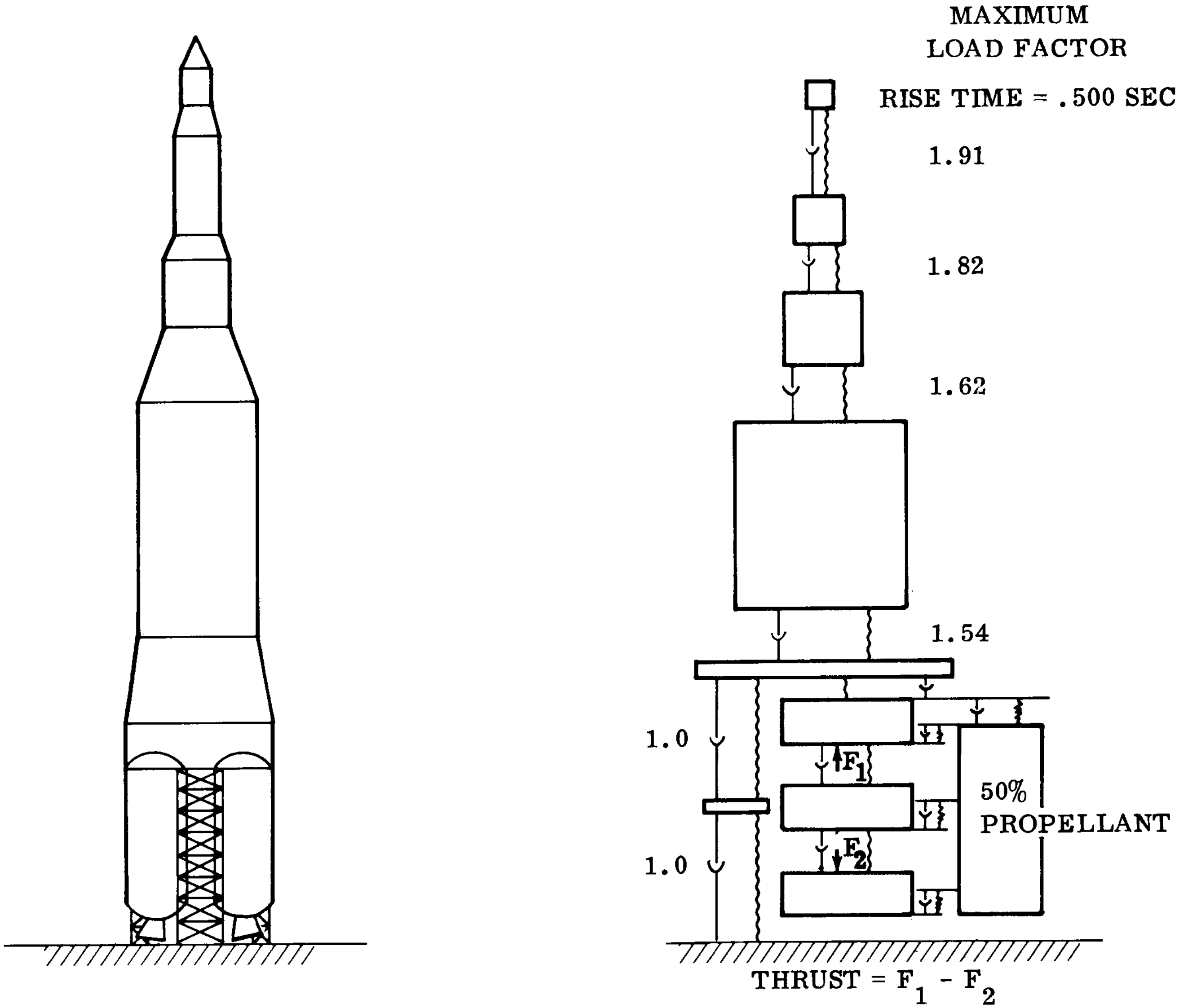
Symmetrical Firing,
500K Vehicle

The space frame model shows higher load factors than the skirt support model. It is expected that this trend can also be expected from the tower support concept. This may be attributed to the greater motion of the first stage before lift-off which occurs in the space frame model. This motion results from the unloading of the initial compression in the frame and is the primary factor in the dynamic magnification of loads.

These load factors were based on a static deflection of the frame of 4 inches. Subsequent sizing shows that this deflection will be about 8 inches. It is anticipated from previous trend studies that this larger static deflection would result in even higher load factors.

DYNAMIC MODEL-SPACE FRAME

Symmetrical Firing — 500K Vehicle



STRUCTURE EVALUATION SUMMARY

The cross-beam structure evaluation chart reflects some of the parameters evaluated in the structural design studies. The chart presents only the product of the cross-beam cluster structure evaluation. The 125K vehicle, effects of fins, barrel concepts, and other cluster arrangements and concepts are also being evaluated. These evaluations generally follow the trends reflected on the chart.

The inert weight changes are relatively insensitive to structural design, as shown by percentage change in payload of the baseline vehicle. Most of the other comparisons reflect little decisive data.

The most significant criterion presented is the rating given the structural arrangements under the title of "Pad Assembly and Logistics." This rating also appears to summarize present estimates of total system rating which are being established by evaluating major parameters such as launch facilities and operations, vehicle transportation, maintainability, vehicle assembly, pad occupancy time, alignment and indexing, fabrication of detail parts and subassemblies, and fin adaptability. A cost evaluation has not been completed. The influence of cost and additional considerations of fin requirements may revise the total system ratings. Therefore, the system rating is tentative and may be revised with additional study.

The first place rating appears sufficiently firm to tentatively conclude that the preliminary design activity will be conducted for both vehicles using the cross-beam structure with one-end-fixity and skirt support with three-point support per motor. It is anticipated that fins will be required.

CROSS BEAM STRUCTURE EVALUATION

500K Payload (Baseline) -- No Fins

Tandem Staging -- (4) 260 In. Dia. Motors

Structural Configuration		Inert* Weight (Pounds)	Perform Effects % Changes In Payload	Max. Sym. Starting Load Factor (g's)	TVC Adapt.	Pad Assembly and Logistics [3]	Cluster Growth	Total System Cost
Skirt Support	One-End Fixity	108,000	+ 0.80	3.78**	[1]	1	All Concepts Are Feasible	——
	Two-End Fixity	123,000	+ 0.53	——	[1]	3		——
	Shear Ties	98,000	+ 0.98	——	[1]	2		——
Space Frame Support	One-End Fixity	163,000	- 0.2	4.0**	[2]	7	Growth In Number of Motors And Motor Thrust Level Is Possible	——
	Two-End Fixity	——	——	——	[2]	8		——
Interstage Support (Tower)	One-End Fixity	128,000	+ 0.45	3.0**	[1]	4		——
	Two-End Fixity	——	——	——	[1]	6		——
	Shear Ties	——	——	——	[1]	5		——

* Baseline Inert Weight = 153,000 Pounds

** Load Factor After Lift-Off At Base of Payload

[1] Good Except Vectrol

[2] Liquid Tankage And Vectrol Create Space Problem

[3] includes:
Launch Facilities & Operations
Vehicle Transportation
Maintainability

[redacted]

BLANK

SUBSYSTEMS

2B-21847-82

MOTOR DIAMETER EFFECTS

The general configuration of a baseline vehicle for the 500K payload was established early in the studies. Characteristics of this vehicle, including first stage motor diameter, were determined by rudimentary analysis. A more refined analysis of first stage motor diameter effects has since been completed.

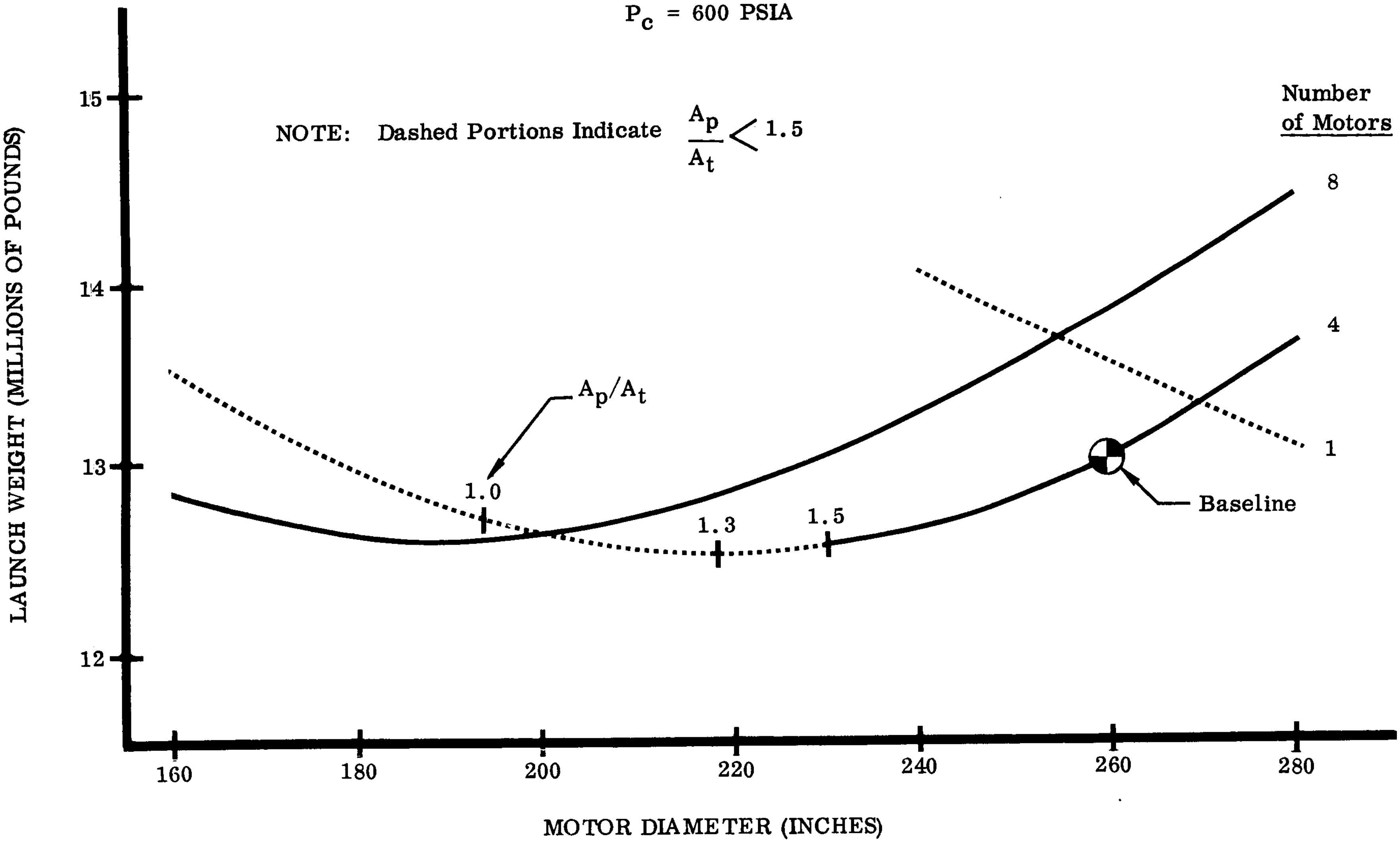
Variation of vehicle launch weight with first stage motor diameter for a chamber pressure of 600 psia is shown in the chart. Variations with chamber pressures of 500 and 800 psia (not shown) were also determined. Vehicles having first stages with 1, 4, and 8 motors were considered.

In the chart, port-to-throat area, A_p/A_t, limitations are shown. Thus, the minimum launch-weight vehicle with four motors occurs when A_p/A_t is approximately 1.3 and the motor diameter is 220 inches. A conservative lower limit of 1.5 was assumed. Thus, the minimum allowable launch-weight vehicle, with a chamber pressure of 600 psia, is obtained when the motor diameter is slightly higher. The launch weight of the baseline vehicle is indicated for reference.

MOTOR DIAMETER EFFECTS

500 K Vehicle

P_c = 600 PSIA



CHAMBER PRESSURE OPTIMIZATION

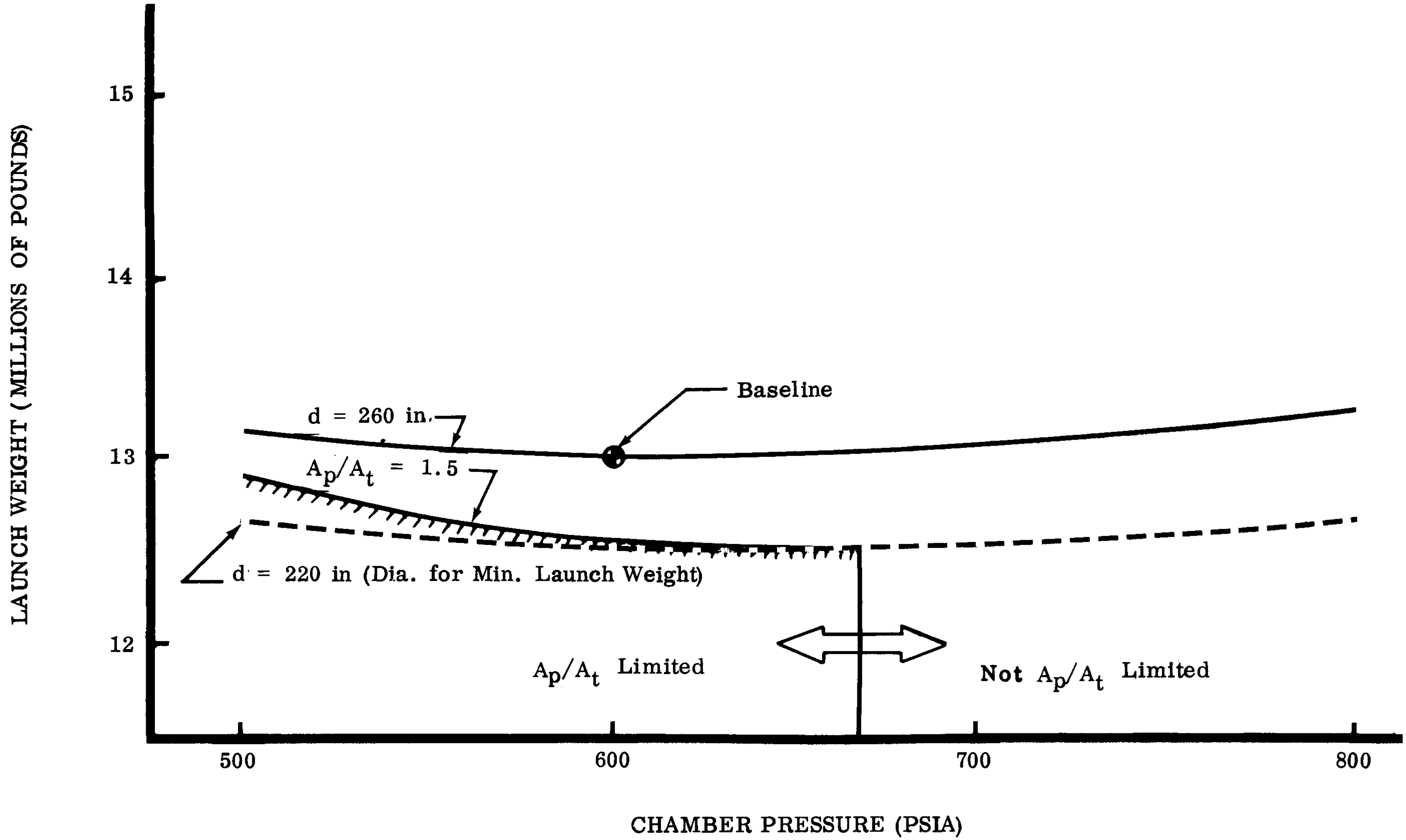
For a cluster of four motors in the first stage, launch weight is not very sensitive to chamber pressure. The chart shows the launch weight variations for vehicles using the 260-inch motor and the 220-inch motor. Use of the latter motor was shown to yield the minimum launch weight vehicle independent of chamber pressure. As the preceding chart indicated, for a chamber pressure of 600 psia, a port-to-throat area ratio limit of 1.5 precludes selection of the diameter for minimum launch weight. For chamber pressures below approximately 670 psia, port-to-throat area ratio is the limiting parameter on selecting motor diameter for lowest launch weight. For chamber pressures greater than 670 psia, port-to-throat area ratio is no longer a limit.

Study results indicate, if the possibility of payload growth is not a factor, the optimum solid-motor diameter for the 500K payload is approximately 220 inches and chamber pressure should be approximately 600 to 700 psia. However, only a minor launch weight penalty is incurred by designing to 260-inch motors.

CHAMBER PRESSURE OPTIMIZATION

500 K Vehicle

Cluster of Four Motors



TAILORING FIRST STAGE THRUST — TIME HISTORY

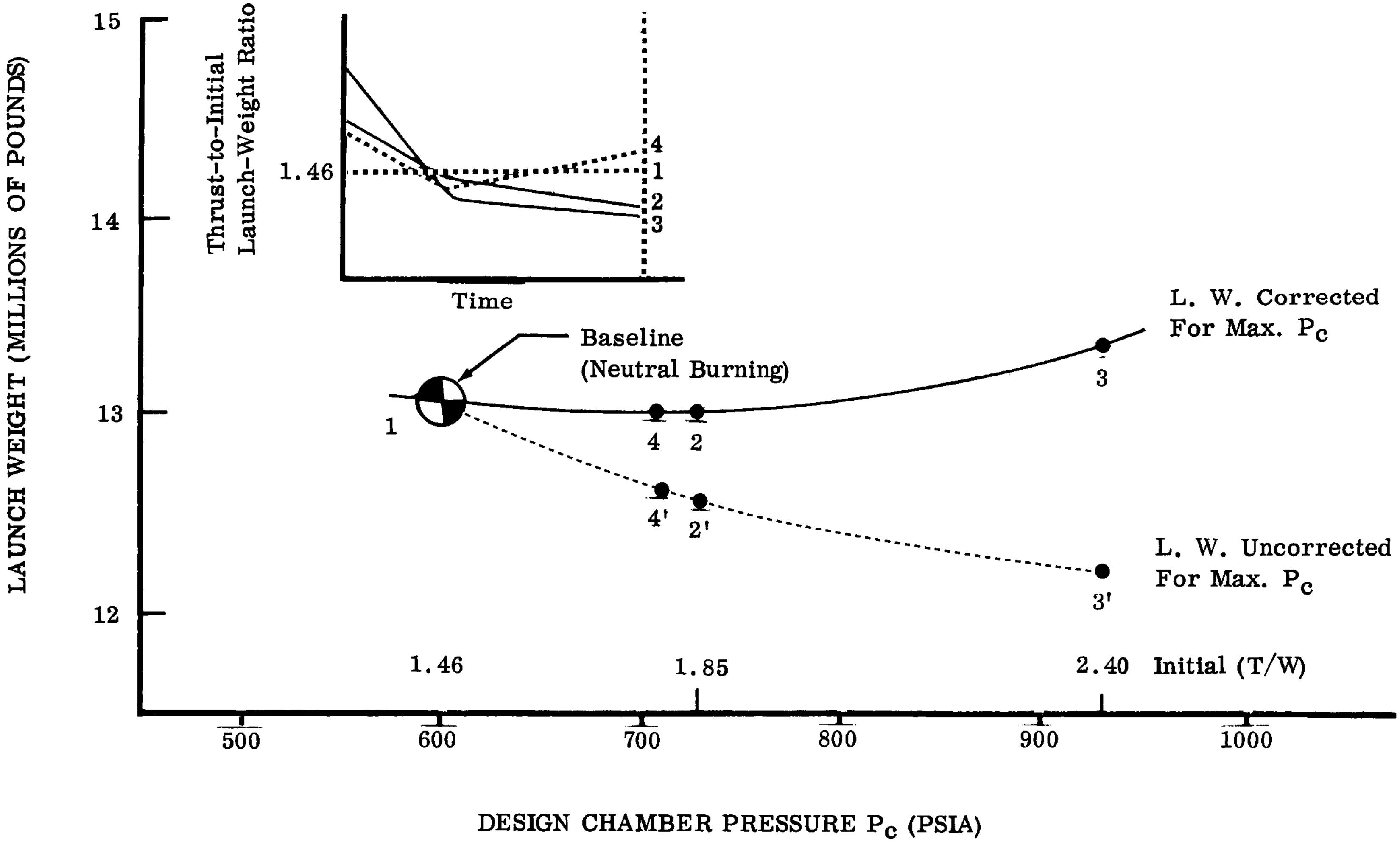
From a performance standpoint, a high initial thrust-to-weight ratio is desirable, but results in excessive maximum dynamic pressure for neutral burning propellant grains. Previous studies indicated that tailoring of first stage thrust-time curve would allow retention of the desired initial thrust-to-weight ratio and also comply with q_{max} limitations. These previous studies compared a neutral burning with a saddle-shaped thrust-time curve, curves 1 and 4 on the thrust-time inset. Corrections for design P_c were not made.

Results of the previous studies are exemplified by a comparison of the performance of a neutral burning grain, point 1, with a saddle shaped grain with no corrections for the higher maximum chamber pressure, point 4′. Present studies indicate further gains as the thrust-time variation is changed to a regressive type, points 2′ and 3′, again with no corrections for maximum chamber pressure. As the chart indicates, the inert weight (hence, launch weight) was not corrected for the increasing design chamber pressure. When the effects of increased design chamber pressure are taken into account (points 2, 3, and 4), there is little or no performance gain; and, as point 3 indicates, there may actually be a loss. Second stage parameters remained fixed throughout.

[redacted]

TAILORING FIRST-STAGE THRUST-TIME HISTORY

500K Vehicle



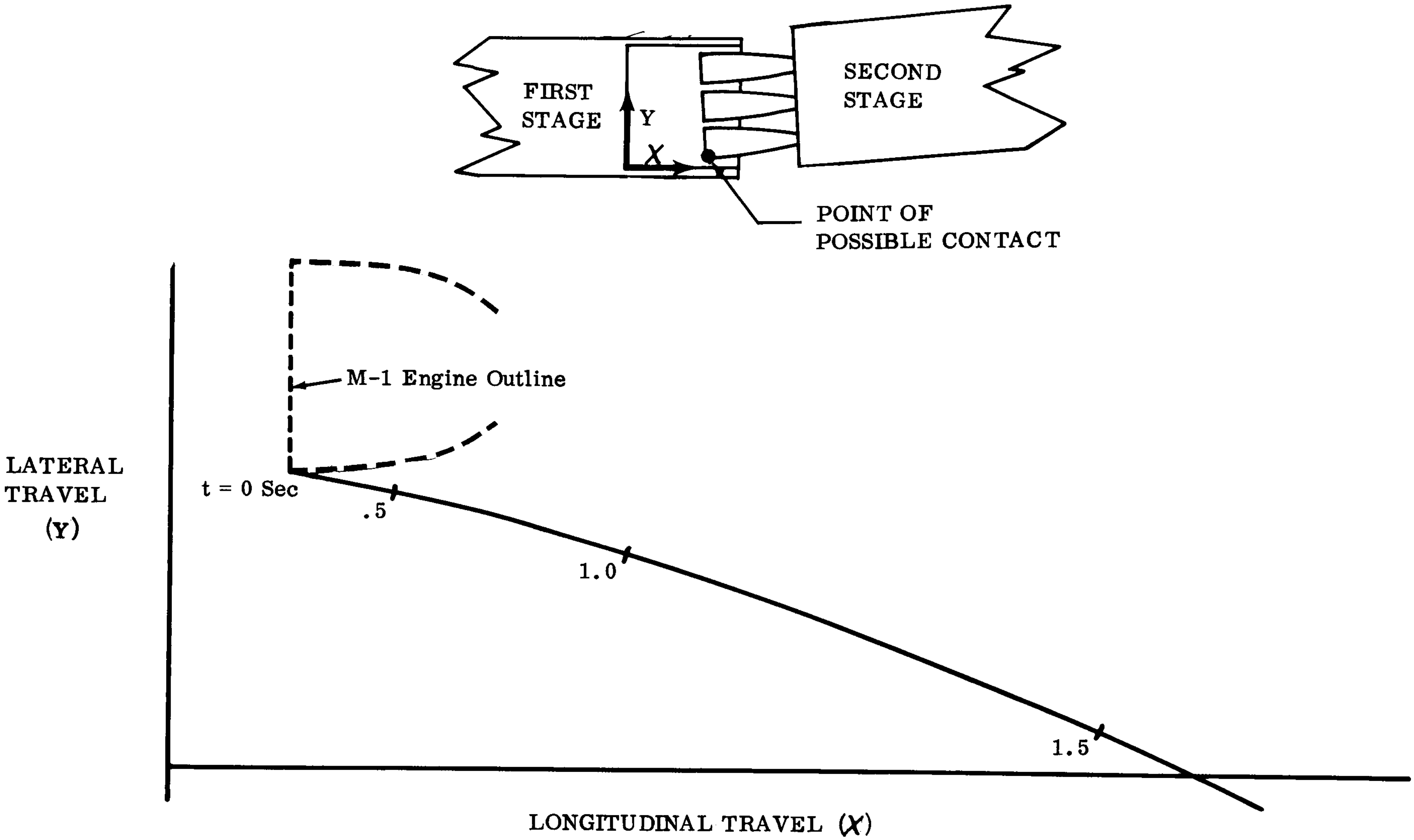
[redacted]

STAGE SEPARATION CLEARANCE

Preliminary studies of the motion of second stage engines with respect to the first stage interstage structure are being performed. These studies, concerning the baseline 500K vehicle, will define separation clearance problems. Effects of aerodynamic loads on the two stages, first stage retrorocket and second stage ullage rocket thrusts, and of first stage motor variances and other perturbations are being considered.

The analytical results will be prepared in the form of X-Y clearance graphs as indicated in the chart. These graphs are uniquely associated with a given vehicle configuration. Thus, extrapolation and/or iteration of the preliminary results will be required to define separation characteristics of the final or recommended 500K vehicle. This definition, based on trade studies, will include total thrust and duration of retro units, choice between single and dual plane separation, and the sequence of separation events.

STAGE SEPARATION CLEARANCE



STAGE SEPARATION METHOD

The final type of interstage structure and the number of separation planes will be determined in the next study phase. Preliminary studies of the methods for physical separation have been conducted. Stringer and frame structure and a single separation plane were assumed.

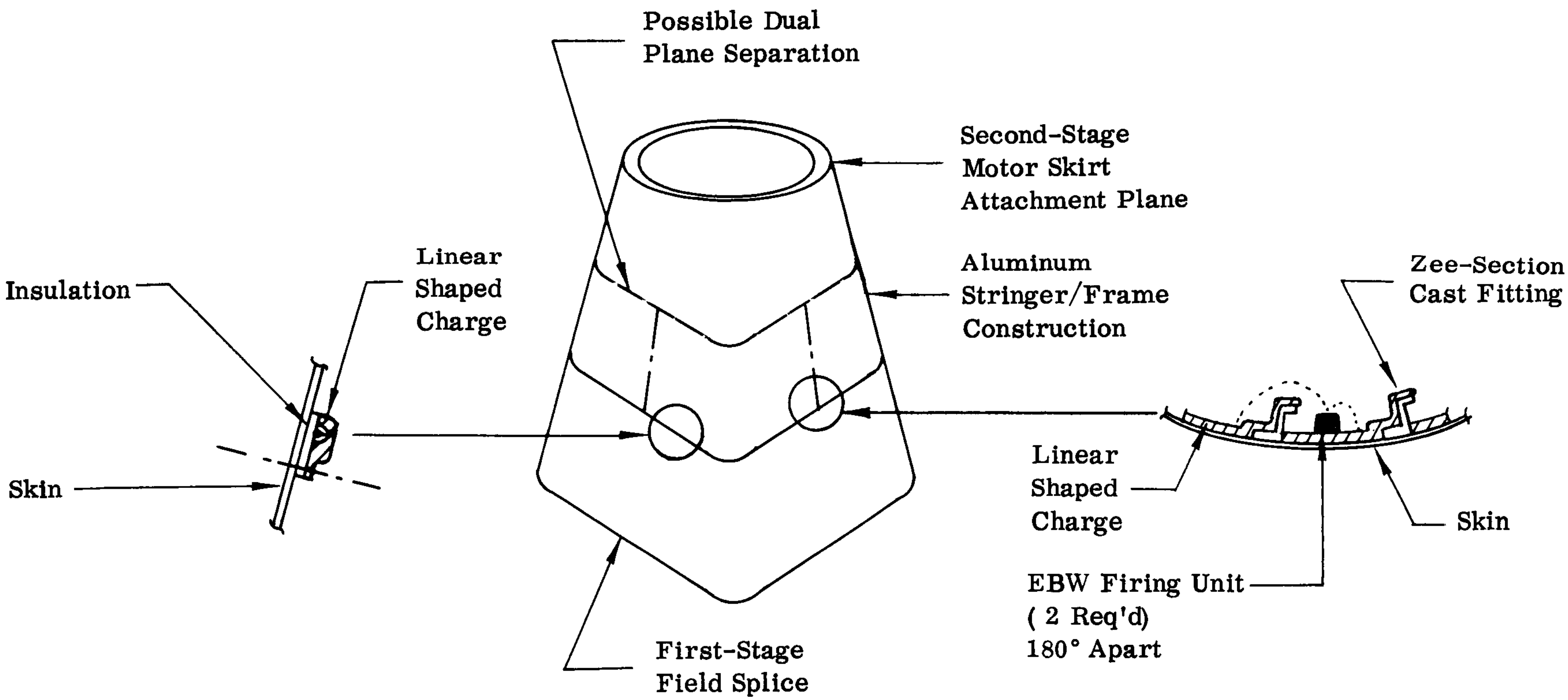
The use of explosive bolts, the pressure separation technqiue, and linear shaped charges were considered. Of these techniques the linear shaped charge is believed to be the best for interstage separation of large boosters.

To design a redundant system using explosive bolts, two ignition points are required for each bolt. The reliability of this system decreases with the number of bolts because every bolt must function for satisfactory operation of the system. Dual plane separation would aggravate this problem.

The pressure separation technique would require a special design for the interstage structure. At present, the state of the art for this technique is not sufficiently advanced. Control of a dual plane separation would be difficult.

The linear shaped charge does not require as many initiation points as the explosive bolt technique. The reliability of the system can be increased by redundant firing circuits. Also, small discontinuities in the linear shaped charge will not cause a malfunction because the shock front will propagate and initiate the charge across a crack. For stringer and frame type construction, cutting the stringers imposes the requirement for a large number of explosive interfaces — this is objectionable. Careful inspection, quality control, and redundant charges will offset this objection. The basic linear shaped charge system will require about 100 grains of flexible charge per foot, augmented by specially shaped charge castings at the stringers. Redundant firing units, with doubly redundant exploding bridge wire (EBW) initiators, are recommended. Preliminary calculations indicate thermal insulation is needed between charges and structure because of aerodynamic heating.

STAGE SEPARATION METHOD



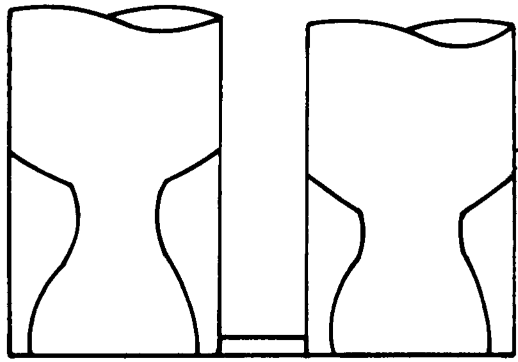
500K VEHICLE BASE HEATING

Initial base heating studies are being made and have resulted in estimates of heating rates at the aft end of the booster.

Radiant heat energy from the jet plume will yield a maximum heating rate of 12 BTU/ft^2-sec to the motor cases at the intersection plane of the cylindrical portion of the case and the ellipsoidal portion of the aft closure.

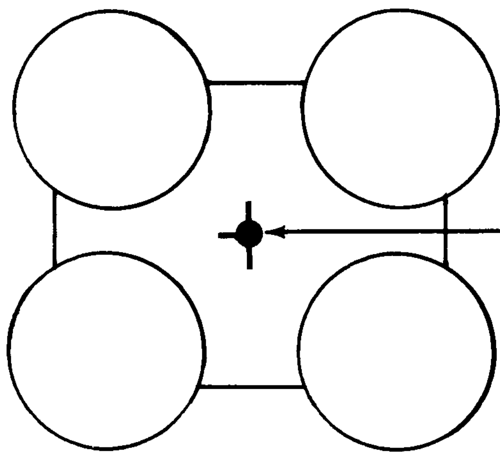
A review of the study vehicle and other vehicles indicates a requirement for a heat shield at the nozzle exit plane to act as a baffle to prevent impingement of the gases against the motor aft closures and the inboard cylindrical sections. The heat shield will be exposed to a maximum radiant heat rate of approximately 35 BTU/ft^2-sec and a maximum convective heat rate of 11 BTU/ft^2-sec. Both values are for a point equidistant from the motor center lines and located in the plane of the nozzle exit areas. The shield will aid in obviating the need for external insulation of the motors. One problem is that some form of fairing will be required on the forward surface of the heat shield for aerodynamic considerations. The fairing and the problems of shielding the components of the thrust vector control (TVC) system will be considered in the final period of analysis.

500 K VEHICLE BASE HEATING



Heat Rate to Case From Jet Plume (Radiation)

$q = 12$ BTU/Ft^2 Sec.



Heat Rate to Base Plate in Plane of Nozzle Exit

Convection

$q = 11$ BTU/Ft^2 Sec.

Radiation

$q = 35$ BTU/Ft^2 Sec.

VEHICLE/LAUNCH PLATFORM INTERFACE

Skirt-Support Cluster Structure

Each solid motor is supported independently on an elevated launch platform by motor base skirt extensions. To provide stability, the lower face of each skirt contains three support pads, equally spaced on the skirt diameter. Support under each pad is provided by a vertically adjustable power-driven jack mounted in the launch support structure. Twelve jacks arranged in four groups will accommodate all the first-stage motors, and will support the static and dynamic loads of the assembled and fueled vehicle.

To ensure that all supporting structure is outside the vehicle lift-off clearance envelope, the vehicle skirt/support jack interface must be located on a level close to the exit plane of the nozzles. Since the size of the jacks prevents location between adjacent motor cases, one of each group of jacks must be positioned at the center of the four motor cluster. These four jacks will be mounted on a fixed supporting column projecting upward through the center of the launch platform. Two outer supports for each motor provide the necessary three-point support and eliminate a requirement for jack coupling.

Positive positioning of each motor on the launch platform will be ensured by a locating pin in the center of each jack. These pins will engage mating holes in the skirt support pads.

Advantages offered by this support system include:

1) Alignment of each motor can be accomplished independently of the others. Movement of one motor does not affect the alignment of the others.

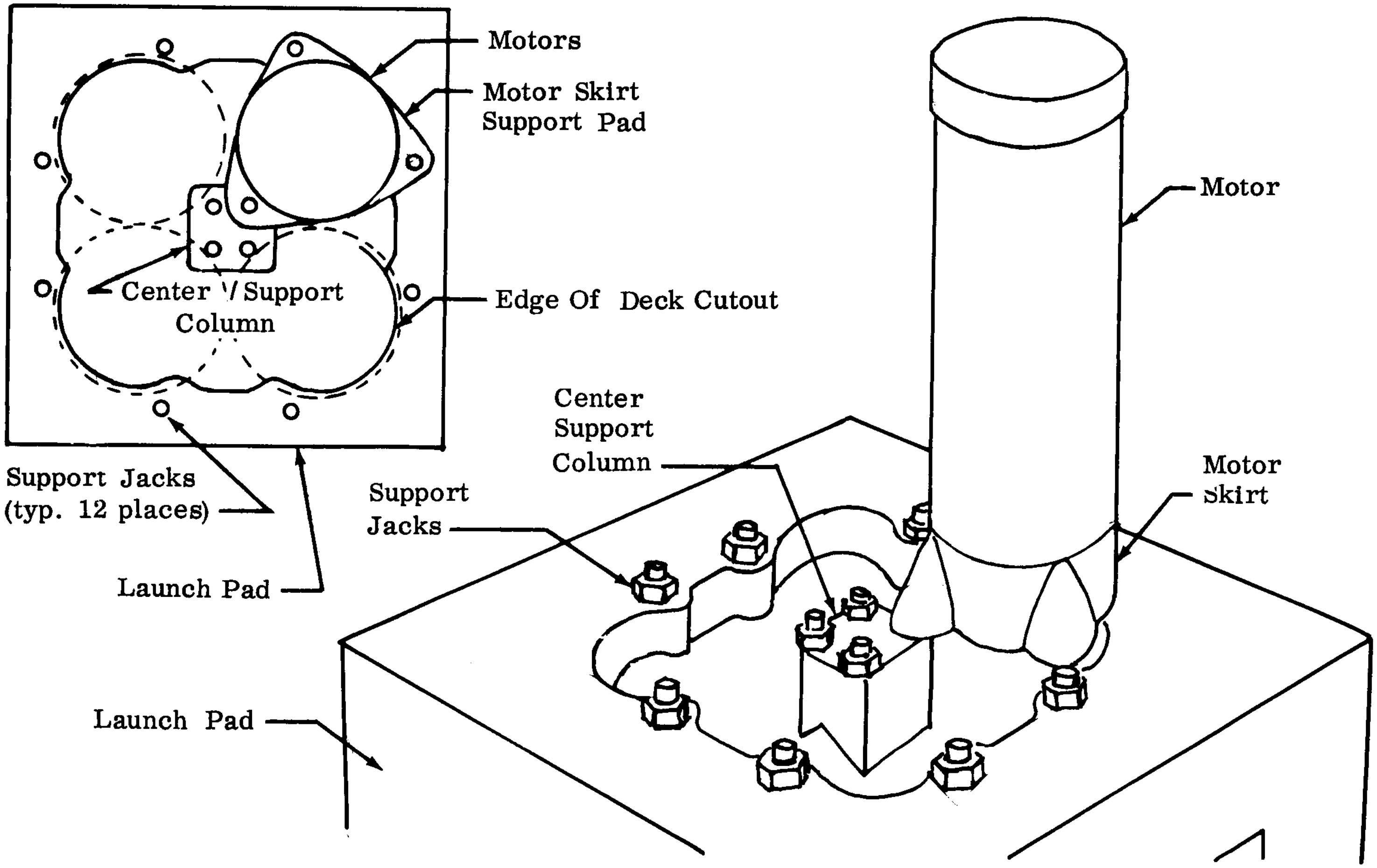
2) Motor load is transferred to the support platform by elevating the jacks. The lifting crane does not deposit the load.

3) No mechanical hold-down locks are required. Individual motors and assembled vehicle are stable on the supports.

4) Vehicle lift-off clearance is unrestricted. No supporting structure projects within the clearance envelope. Addition of vehicle fins will not compromise the clearance.

VEHICLE/LAUNCH PLATFORM INTERFACE

Skirt Support Cluster Structure



MOTOR INSTALLATION AND ALIGNMENT

Skirt Support Cluster Structure

A mobile gantry crane will lift each motor vertically from a transport barge and place it over its position on the launch platform. The side legs of this crane will straddle the launch support platform. The crane will then lower the motor to within several inches of its final position. The supporting jacks will then be driven upwards until they contact the pads at the base of the motor skirts. During this movement, a tapered pin in the center of each jack will enter a mating hole in the pad, causing the motor to shift into position. Transfer of the motor load will be accomplished by slackening the crane hoisting cables.

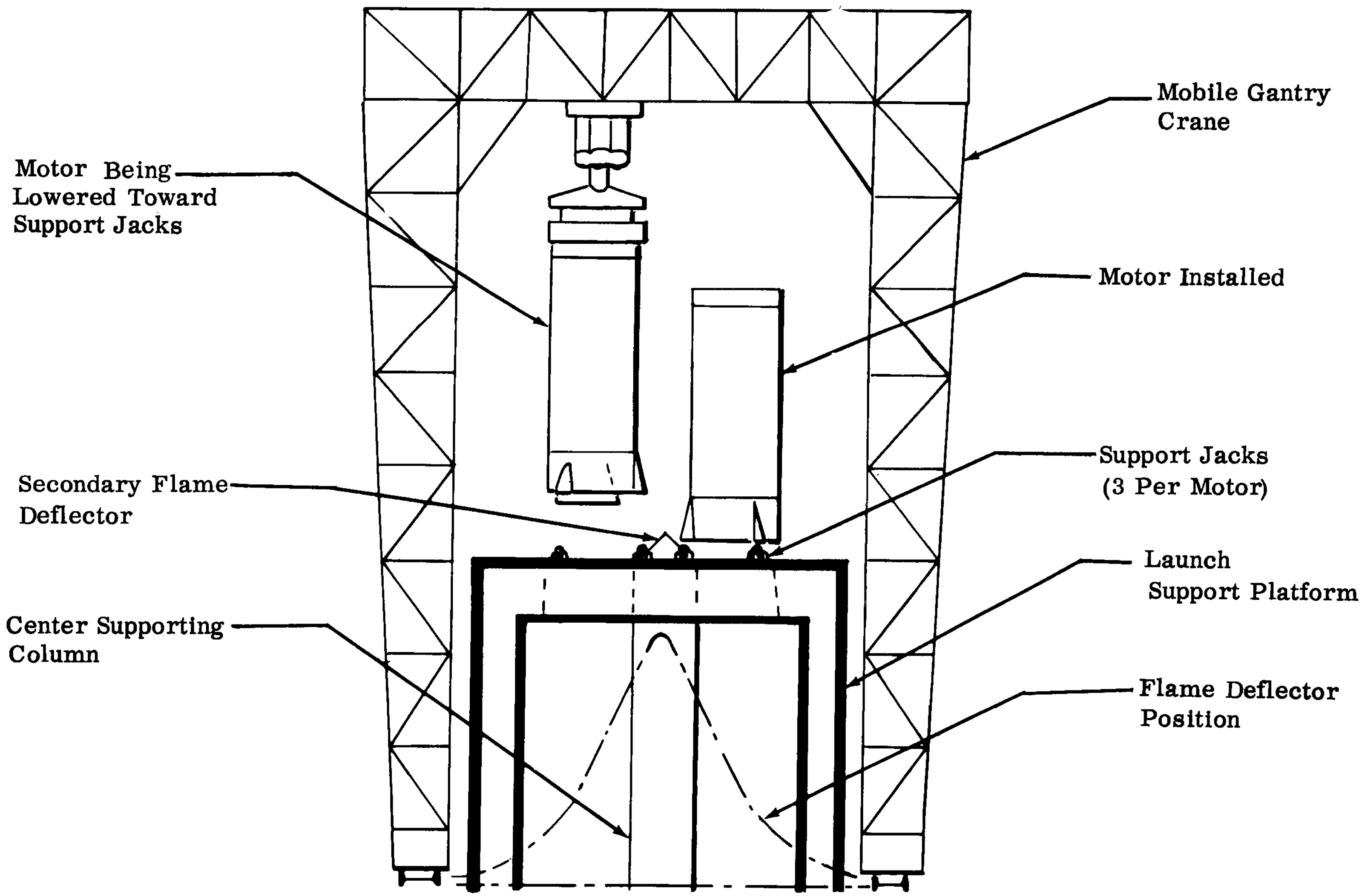
After the motors are installed, they will be aligned by the jacks so that their top mating joints are on a common plane at the proper height above the platform and in correct horizontal relationship with each other. The upper beam tie and shear ties will then be installed to complete the first stage assembly.

A problem does exist with respect to platform structural deflections under the vehicle supporting jacks. Unequal deflections occurring during motor emplacement are compensated for by adjustment of the jacks. Further deflections occurring during upper stage assembly and fueling cannot be compensated. This condition requires that the supporting structure be primarily designed to rigid deflection criteria. To ensure adequate support, it may be necessary to install vertical load struts under all jack positions, extending upward through the flame deflector openings.

In addition, the center column and inside group of four jacks are subject to motor exhaust heat and erosion as the vehicle lifts off. These conditions may be alleviated by partially enclosing the jacks in a pyramid-shaped secondary flame deflector placed on top of the column.

MOTOR INSTALLATION AND ALIGNMENT

Skirt-Support Cluster Structure



VEHICLE/LAUNCH PLATFORM INTERFACE

Space-Frame Cluster Structure

The principal feature of the space-frame support concept is that the solid motors are not mounted directly on the launch support platform. Each motor, instead, is suspended by its top skirt extension between two wings of a vertical frame composed of trusses and panels arranged in a cruciform pattern. Four of these wings, or vertical extremities, extend the full length of the first stage and each terminates in a base supporting pad.

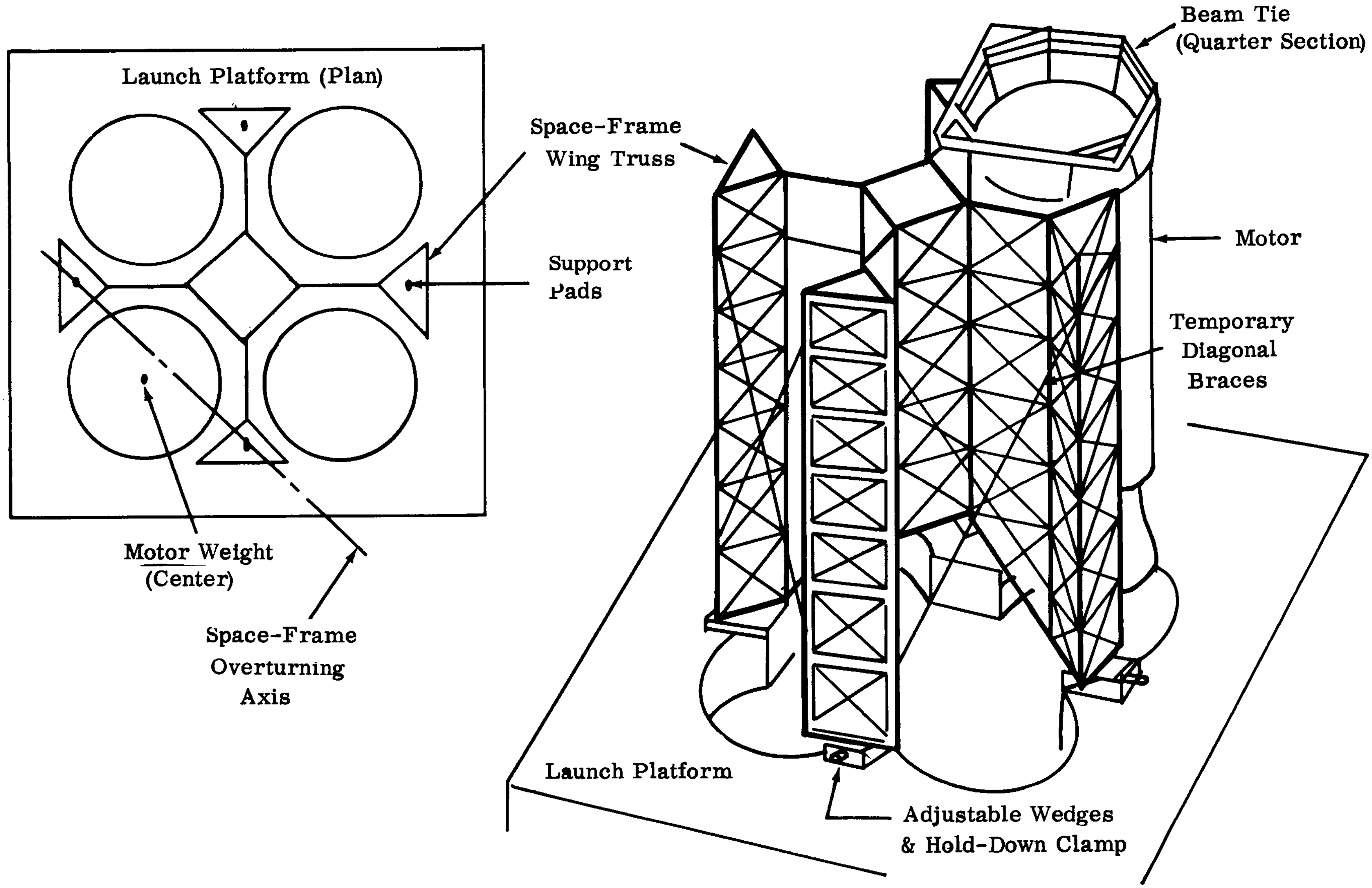
Consideration of the vehicle lift-off clearance envelope requires that the interface level of these pads be located at a level close to the exit plane of the nozzles. In addition, because of the distribution of motor load centers outside of the square pattern of support points during emplacement of the first motor, the space frame will tend to tip off its supports. Positive hold-down locks are therefore required.

Within these restrictions, support of the entire vehicle will be provided by four adjustable wedge blocks mounted on the launch support platform, each containing a center locating pin. The space frame will be placed on the supporting wedge blocks, its position on the platform being established by the locating pins entering mating holes in the frame's base support pads. The wedges will be raised or lowered as required to align the space frame to its proper vertical and angular position. The frame will then be locked down and the four motors installed. Since the hold-down locks are not required to ensure stability of the assembled vehicle, they must be removed before launch.

Advantages offered by this support system include: (a) all supporting members are outside of the main stream of the motor exhaust plumes; and (b) vehicle lift-off clearance is unrestricted. No supporting structure projects within the clearance envelope. Addition of vehicle fins will not compromise the clearance.

VEHICLE/LAUNCH PLATFORM INTERFACE

Space-Frame Cluster Structure



MOTOR INSTALLATION AND ALIGNMENT

Space Frame Cluster Structure

One quarter section of the space frame's top beam tie will be mated to the top skirt extension of each motor before installation. A mobile gantry crane will lift each motor vertically by a handling frame attached to the quarter section, and position it within the vertical wings of the space frame. The motor will then be slowly lowered into position. Although guiding fixtures can be temporarily attached to the space frame, the operation will require precise and delicate handling of the motors by the crane.

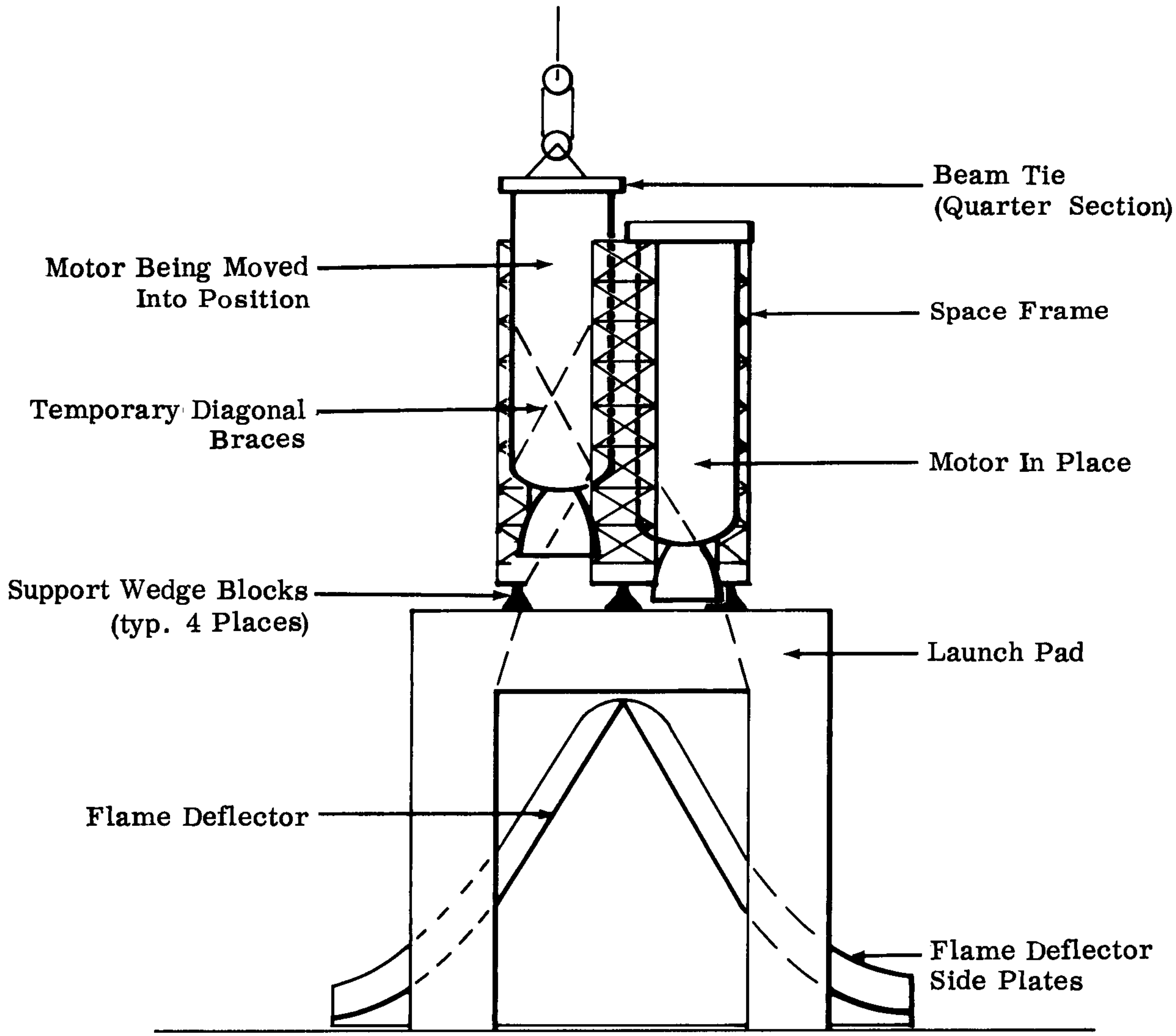
An additional problem encountered is the inherently low torsional strength of the space frame prior to complete assembly of the first stage. This condition requires that temporary diagonal bracing be installed between adjacent outside space-frame trusses to resist inadvertent torsional loads applied during assembly. This condition is most critical after the installation of the first motor. The braces will be removed progressively as the motors are installed.

Alignment of the motors on the space frame must be accomplished when the motor is still supported by the crane. Proper orientation of the motors on the space frame will be ensured by centering pins located at the top of the frame. These pins will enter mating holes in the quarter sections as the motors are being lowered. Final alignment may require shimming at the space frame/quarter-section interface to obtain proper centerline verticality.

The alignment process is further complicated by structural deflections of the space frame and the launch support platform. As each motor is emplaced in its turn, its weight will cause a slight shifting of the others. As with the skirt support concept, this effect may be minimized by designing the support structure to rigid deflection criteria, and installation of vertical load struts under two wedge positions.

MOTOR INSTALLATION AND ALIGNMENT

Space-Frame Cluster Structure



VEHICLE/LAUNCH SUPPORT INTERFACE

Interstage Cluster Structure

In the interstage cluster structure concept, each motor is suspended by its top skirt from an upper beam tie, or interstage, which ties the motors together. Consequently, the interstage must be located upon a launch support structure before motors can be installed. This support is provided at the four corners of the interstage frame by arms mounted on four supporting towers. Based on the flame deflector requirements analysis, these towers are approximately 175 feet high.

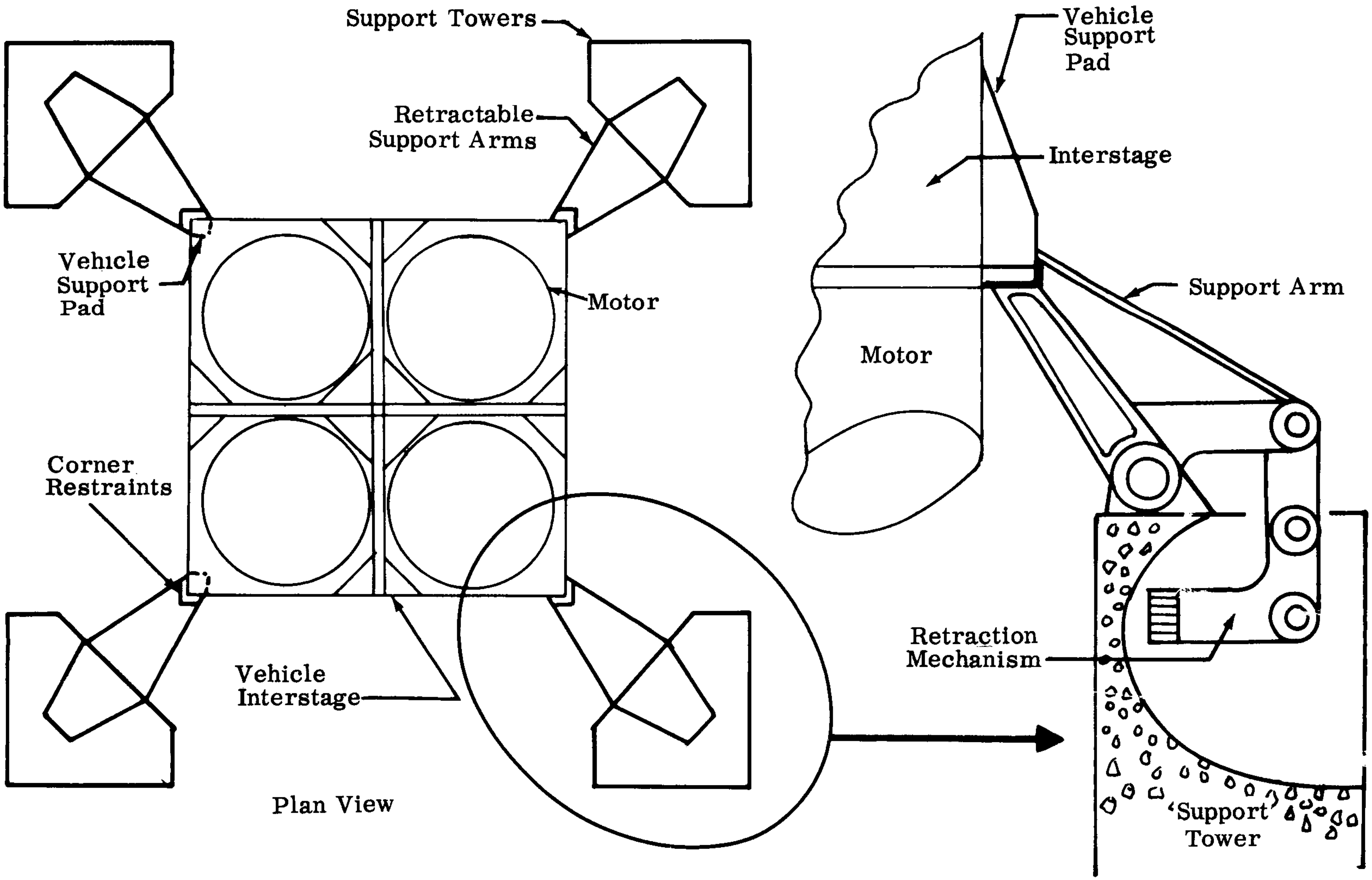
Because the tower structures must be placed outside of the vehicle lift-off clearance envelope, the support arms must be extended inward to pick up the support points. This extension results in a 16-foot cantilevered arm for the 5-degree clearance angle established as a criterion for lift-off with all vehicle systems operating. Failure of one motor to ignite may result in a total side-drift angle of about 15 degrees, requiring a cantilever of 34 feet. The support arms must be capable of retraction within the lift-off time and envelope restrictions. Retraction of the arms can be accomplished by mounting them in trunnions installed on the towers. Counterweights will cause rotation by gravity upon vehicle lift-off, with assistance from positive mechanical means to ensure retraction in time. The basic clearance problem will be considerably increased should vehicle fins be required.

Positive location of the interstage on the support structure will be established by means of corner restraining members on the top resting surface of the cantilever arms. These members will confine the interstage within the proper horizontal limits.

Advantages offered by this support system include: (a) all supporting members are outside of the main stream of the motor exhaust plumes; (b) access for a single piece, two-way flame deflector is good; and (c) a solid motor may be removed from the assembled vehicle without prior dismantlement of the upper stages although special equipment would have to be developed for this purpose.

VEHICLE/LAUNCH SUPPORT INTERFACE

Interstage Cluster Structure



MOTOR INSTALLATION AND ALIGNMENT

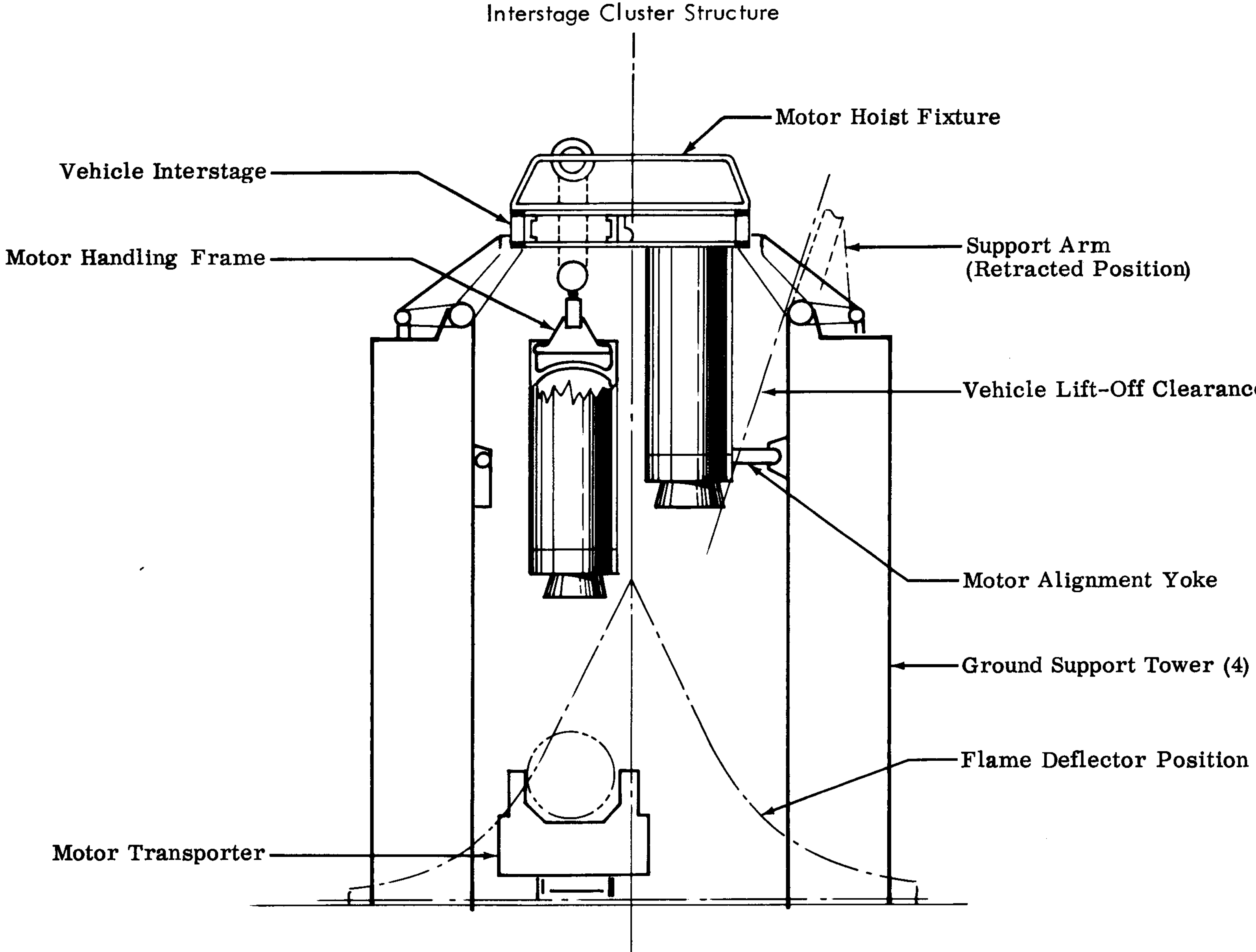
Interstage Cluster Structure

A crane in a vehicle servicing tower will first position the interstage frame on its four supporting arms; the service tower will straddle the four support towers. Since the motors must be lifted into position from below, they must be brought by a transporter directly into position under the interstage. A special handling frame will be mounted to the top motor skirt extention. In order that the mating surfaces of the motor skirt extension flange and the interstage flange will meet, this frame will support the motor at the under surface of the skirt flange. This requires that the frame be collapsible.

The actual lifting operation will be performed by a special motor-hoisting fixture positioned on top of the interstage and supported by the cantilever arms. A block and hook will extend downward through the interstage opening, attach to the handling frame, and raise the motor into position. Mating flanges will be bolted together and the handling frame removed. The hoisting fixture will be rotated to each motor position in turn.

A major assembly problem exists in installing the solid motors. Since they must be lifted into position from below, they must be supported by the hoisting crane during assembly. This requires precise handling of the motor by the hoist to achieve final alignment and mating with the interstage. Securing of bolted connections must be accomplished with the motor still suspended from the hoist. When the motor weight is subsequently transferred to the vehicle interstage structure, deflections will occur in the interstage which tends to displace the base of the motor outwards. As each motor is installed, the process of maintaining alignment of the others is compounded. This condition may be minimized by installing temporary alignment yokes between the support towers and each motor to react the outward load displacement, prior to transfer of the weight to the interstage. These yokes will be retracted upon completion of vehicle assembly.

MOTOR INSTALLATION AND ALIGNMENT



GROUND-SUPPORT EVALUATION FACTORS

The major factors at the launch site which influence selection of a vehicle cluster structure concept are shown. The assigned values were derived from analyses of specific vehicle assembly plans and of launch-site support structures concepts which were sufficiently developed to ensure feasibility.

The costs shown are not for the total launch-site ground system. They reflect only major items which might contribute to significant cost differences in the support concepts. Labor and common equipment are not included. In comparing the interstage concept with the other two, several cost differences were found, but they tended to offset one another. The major cost factors were the deletion of a mobile gantry crane, the increased size of a mobile service tower, and the reduced size of an umbilical tower.

Pad occupancy times and manhours were estimated for operational vehicles; but do not include vehicle servicing, subsystem functional checkout, or integrated systems checkout, as they will be nearly identical for all concepts. Lower occupancy time for the space frame results from the preassembly of some subassemblies and wiring in the frame before delivery to the launch site. Estimated manhours are 1574 for the base skirt, 1410 for the space frame, and 1631 for the interstage concepts.

The reliability factor indicates whether any component of the ground support system might fail during launch, thus degrading overall systems reliability. The interstage support concept requires the retraction of supporting arms immediately after vehicle lift-off. This is also true for umbilical servicing arms, but for these the condition is identical for all concepts.

Qualitative comparison of motor installation and alignment is based on consideration of the relative problems encountered and the techniques developed to position, align, and assemble the first-stage motors. The base skirt concept allows a simple method for transferring motor load to the support platform and individual adjustment of each motor without affecting the position of the others.

Each motor in the base skirt and interstage concepts, when installed on its supports, is inherently stable. The space frame tends to tip off its support when the first motor is installed. Consequently, mechanical hold-downs are required for assembly of the first motor. These hold-downs will be manually removed before actual launch operations.

The stability safety factor reflects the overturning effects of a 125 mph wind on a free standing, assembled, but unfueled vehicle. The safety factor is defined as the quotient of the vehicle's overturn resistance moment (due to its weight) divided by the wind overturning moment (total resultant wind force times effective moment arm). Since a factor of two is adequate, all concepts are stable.

500 K VEHICLE CLUSTER STRUCTURE

Ground-Support Evaluation Factors

Cluster Structure	Base Skirt	Space Frame	Interstage
COSTS (Millions of Dollars) Basic Launch-Site Structures	17.7	17.7	16.6
PAD OCCUPANCY TIME (Days) For First Stage Assembly	10.4	9.2	12
RELIABILITY Effect of Support on System	No Effect	No Effect	Support Arm Retraction Failure
MOTOR INSTALLATION & ALIGNMENT	Good	Fair	Poor
MOTOR STABILITY During Assembly	Good	Mechanical Hold-Down Required	Good
STABILITY SAFETY FACTOR For Assembled Dry Vehicle in 125 mph Wind	5.2	3.2	13.5

BLANK

CONTRACT NAS8-2438

TASK NO. 2

LAUNCH WEIGHT AND STAGING ANALYSES

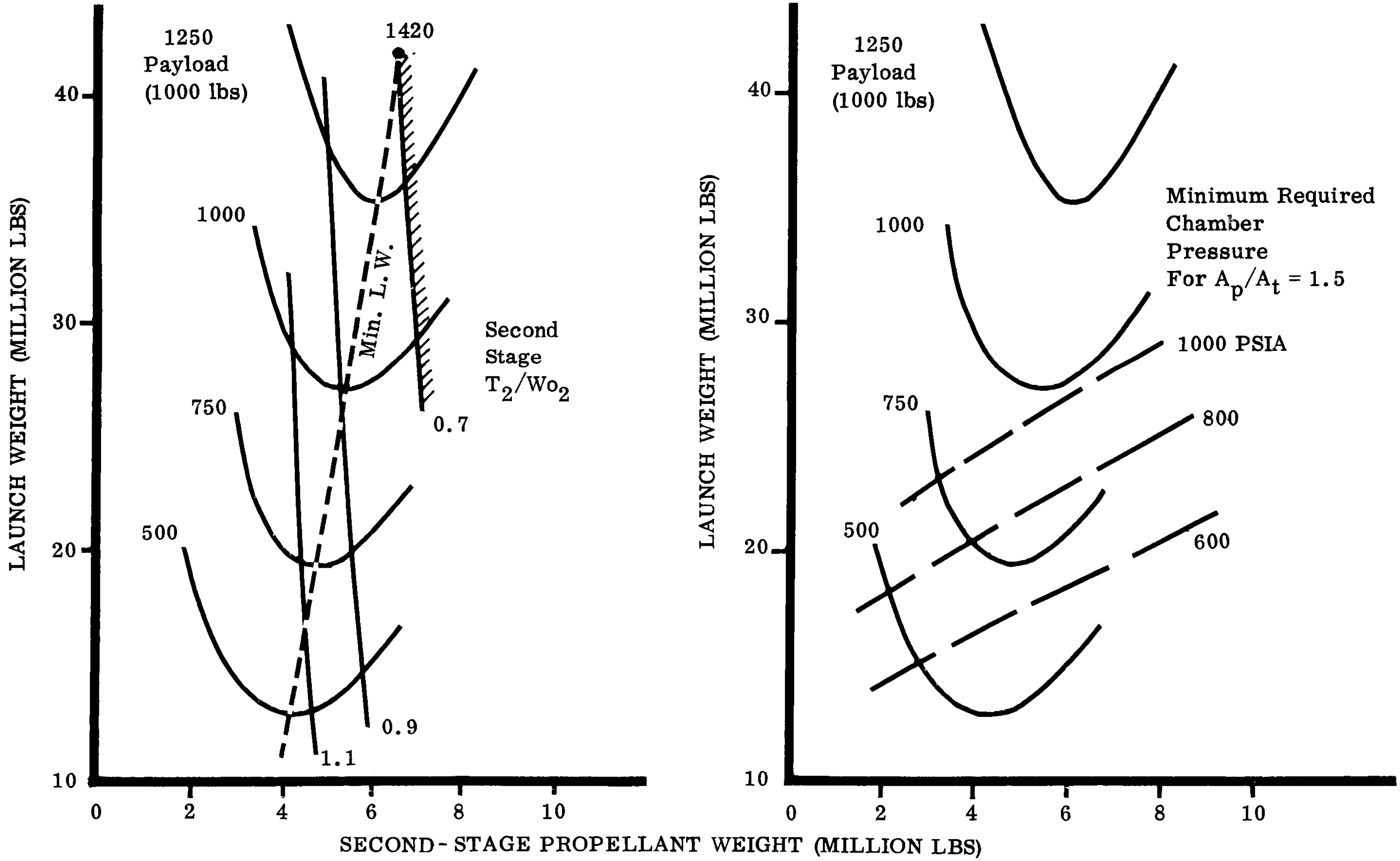
In order to obtain a preliminary overall look at the significance of payload on vehicle size, certain simplifying assumptions were necessary. These include: first stage mass fraction, $\lambda'_1 = .90$; first stage thrust-to-launch-weight ratio, $T_1/W_{o1} = 1.46$ (for $q_{max} = 950$ fps); and five M-1 engines in the upper stage.

The mission is a direct shot into a 177 km parking orbit with the first stage solid and second stage LO_2/LH_2. The launch is due east from AMR.

The effect of propellant staging on the launch weight is shown on the charts for payloads from .5 to 1.25 million pounds. Also indicated are the T_2/W_{o2} and minimum required chamber pressure for a port-to-throat area = 1.5. These limits apply to vehicles with a cluster of four 260-inch-diameter motors in the first stage.

LAUNCH WEIGHT AND STAGING ANALYSES

Preliminary Parametric Results



PROPELLANT WEIGHT AND VELOCITY

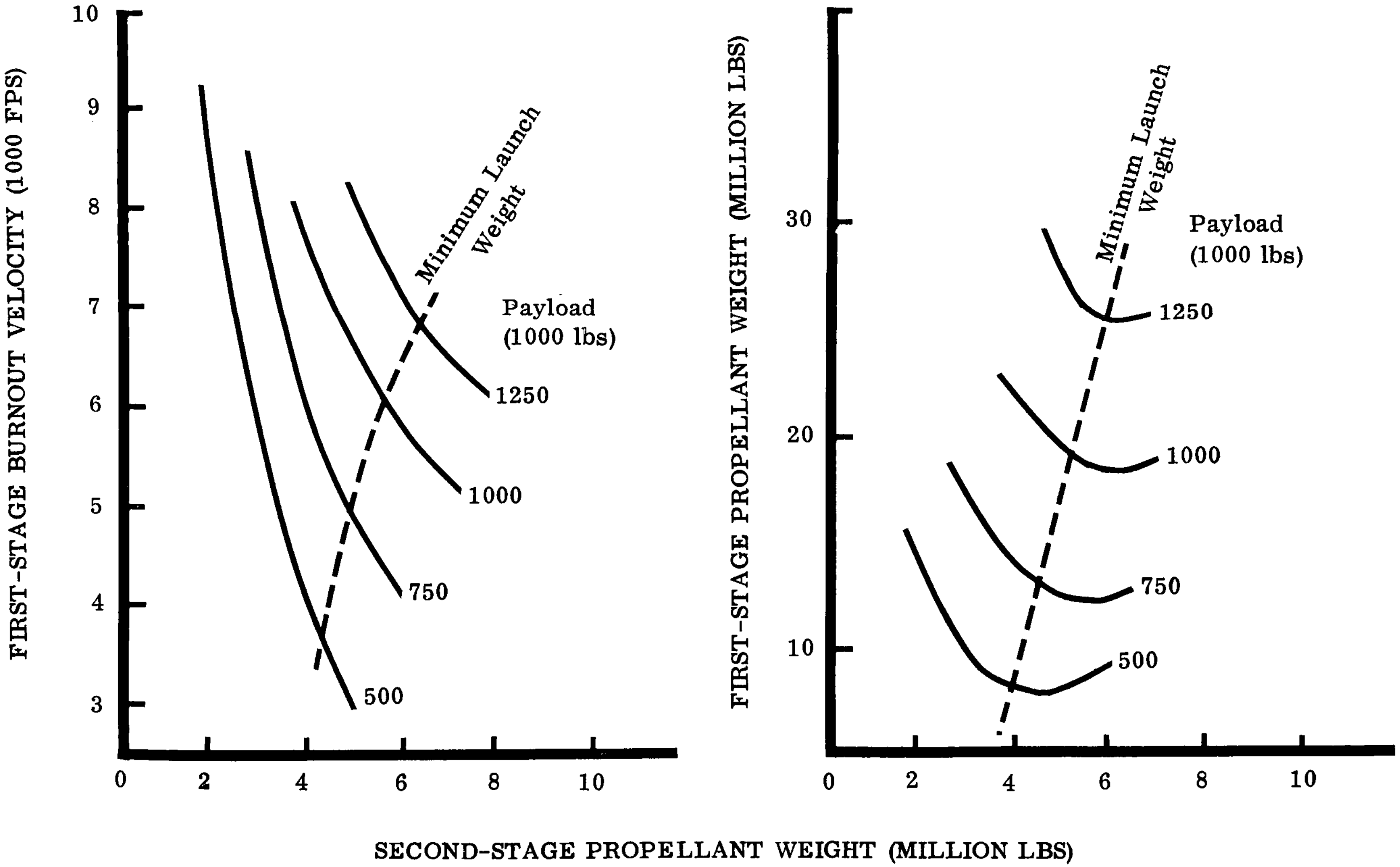
First Stage

These charts are companions to the previous charts since first-stage propellant weight and burnout velocity are shown in place of launch weight. It is interesting that the minimum launch weight vehicle does not occur at the same point as that for minimum first-stage propellant weight.

As the payload increases from .5 to 1.25 million pounds, the first-stage burnout velocity increases from 3600 fps to 6900 fps. At these high payload values, first-stage propellant weight reaches 25 million pounds.

PROPELLANT WEIGHT AND VELOCITY

First Stage



PAYLOAD AND LAUNCH WEIGHT

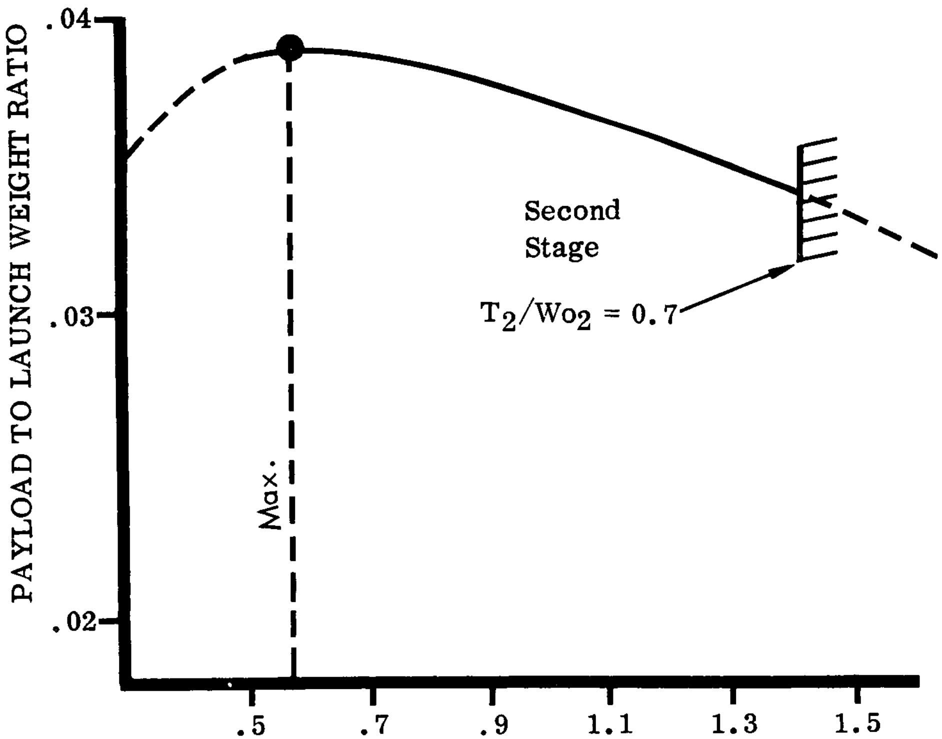
Preliminary Results

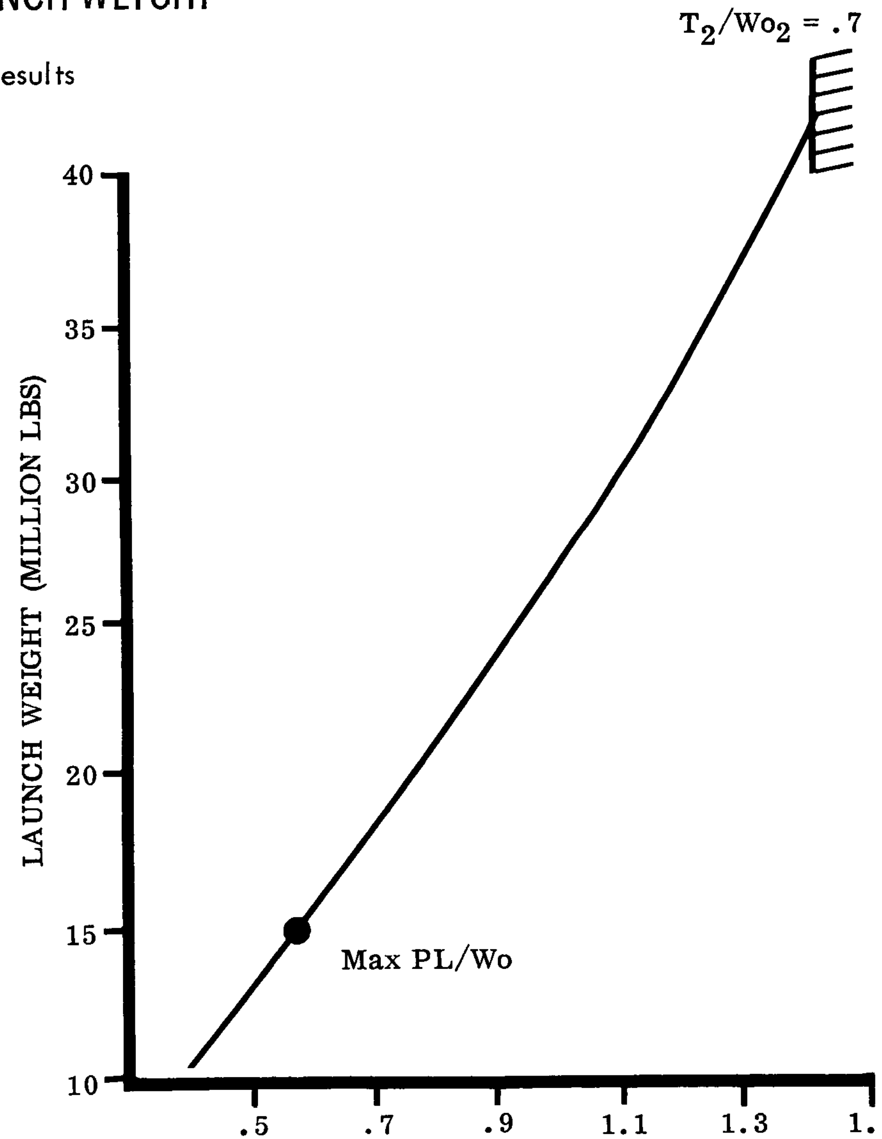
With minimum launch weights determined from previous charts, the effect of payload on launch weight and payload-to-launch-weight ratio (PL/W_{o1}) are shown on the plots. The maximum value of PL/W_{o1} occurs very close to a payload of 500,000 pounds. A lower limit on second-stage thrust-to-weight ratio (T_2/W_{o2}) of .7 is indicated on the charts. (This lower limit will be treated in more detail on later charts.)

The same basic data is presented in terms of launch weight in the parallel chart.

PAYLOAD AND LAUNCH WEIGHT

Preliminary Results





PAYLOAD (MILLION LBS)

FIRST-STAGE BURN TIME AND PROPELLANT WEIGHT

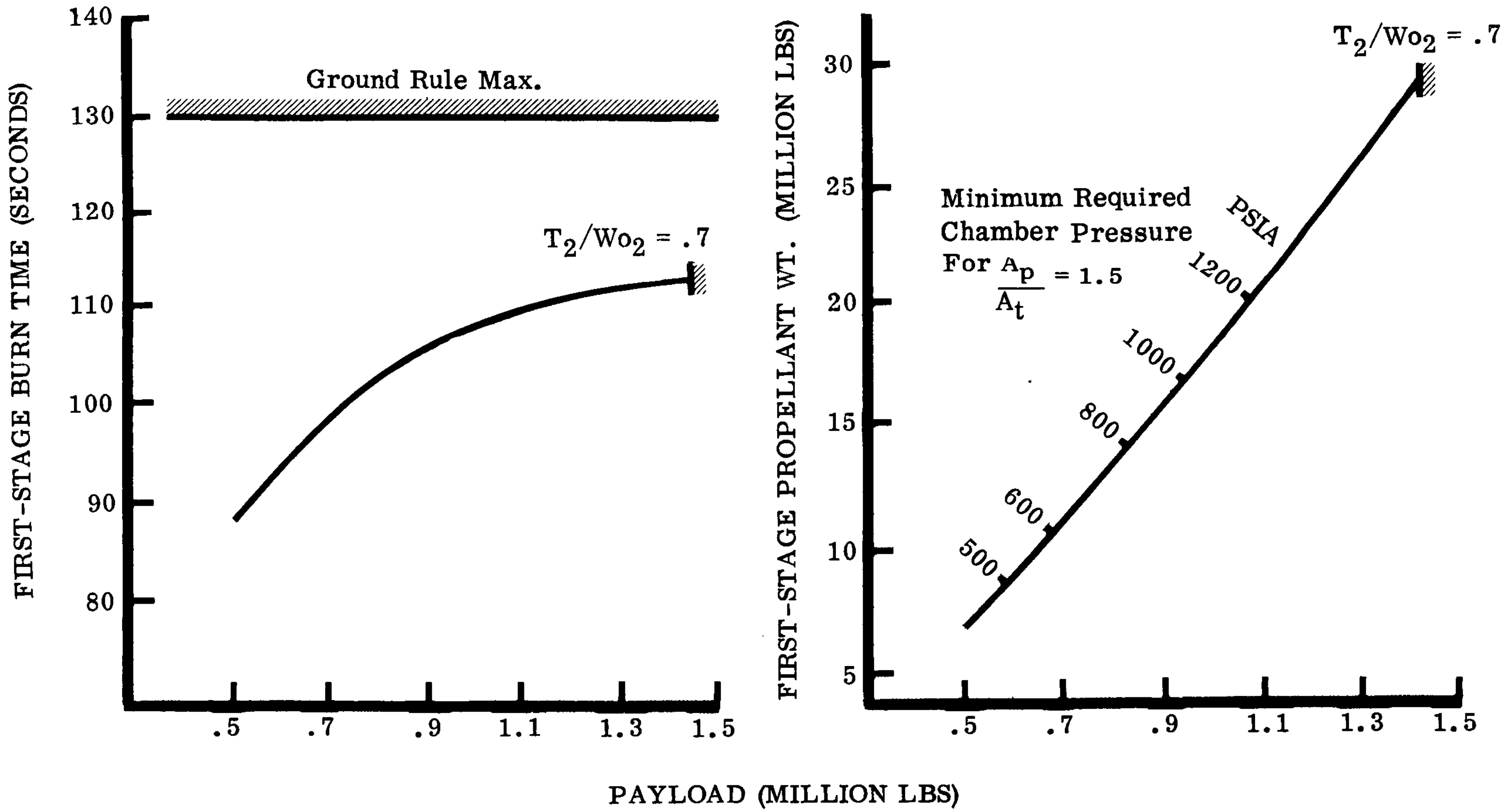
Preliminary Results

Increase in payload results in increased burn time of the first stage for minimum launch-weight vehicles. This is generally to be expected since the thrust of the second stage is held constant (five M-1's). The range of first-stage burn times from 90 to 115 seconds is well within the practical design constraints for solid motors.

The first-stage propellant weight increases with payload; for a payload of 1.25 million pounds, the propellant required is approximately 25 million pounds. Also shown in the chart is the minimum required chamber pressure (a cluster of four 260-inch-diameter motors) for a port-to-throat-area ratio of 1.5. Thus, it appears chamber pressure must be increased as the payload increases.

FIRST STAGE BURN TIME AND PROPELLANT WEIGHT

Preliminary Results



[redacted]

SECOND-STAGE LOSSES

Velocity losses are usually defined as the difference between the ideal velocity and the actual velocity, or,

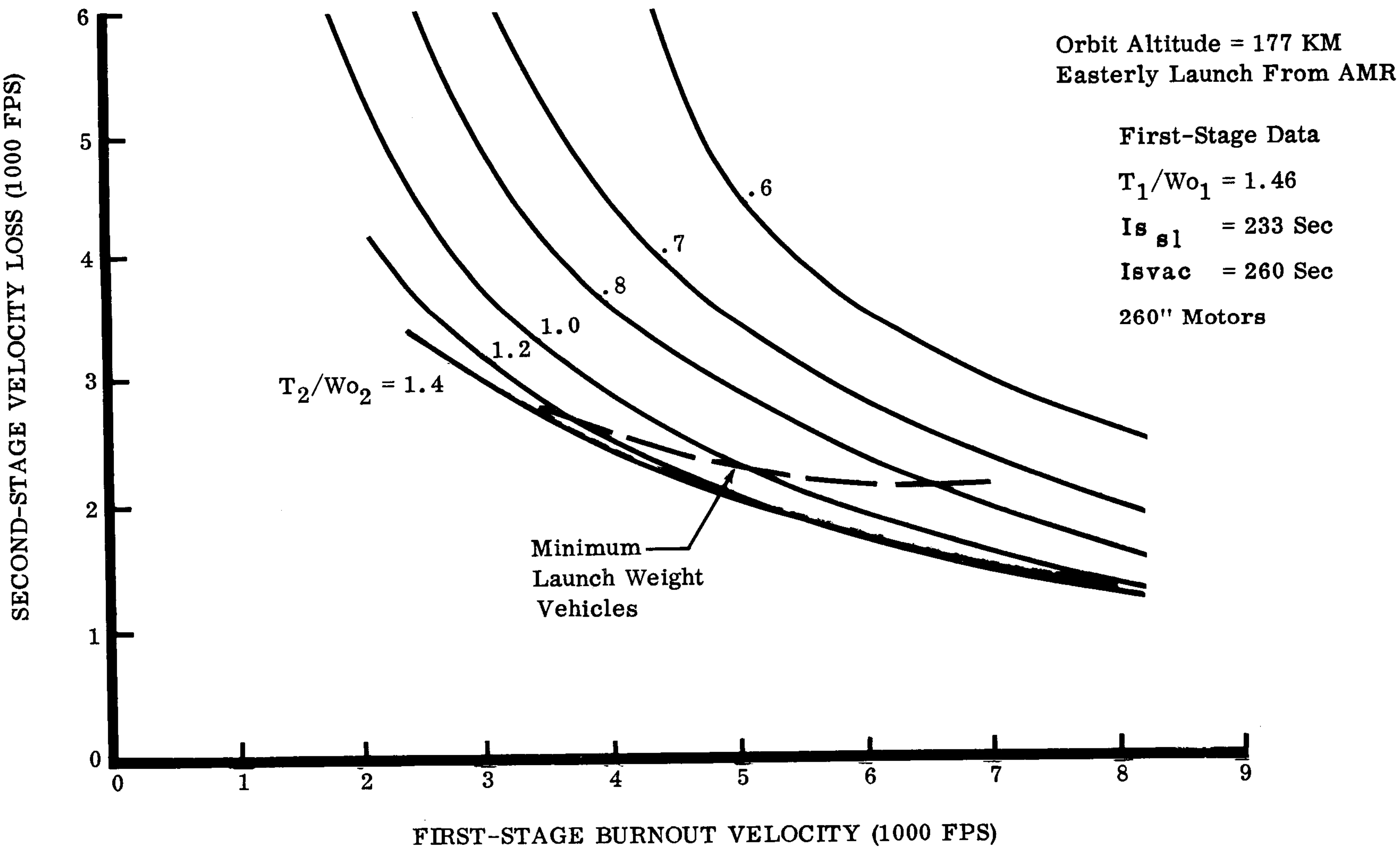
$$V_{Loss} = V_{Ideal} - V_{Actual}$$

$$= gI_s \text{ Log} \left[\left(\frac{W_{initial}}{W_{final}} \right) \right] - V_{Actual}$$

The velocity losses have been determined for the second stage by correlating a series of boost trajectories run on a digital computer. The velocity losses increase as the first-stage burnout velocity or second-stage thrust-to-weight ratio decreases. It is interesting that losses do not vary much for the minimum launch-weight vehicles.

SECOND STAGE LOSSES

Isvac = 425 Seconds

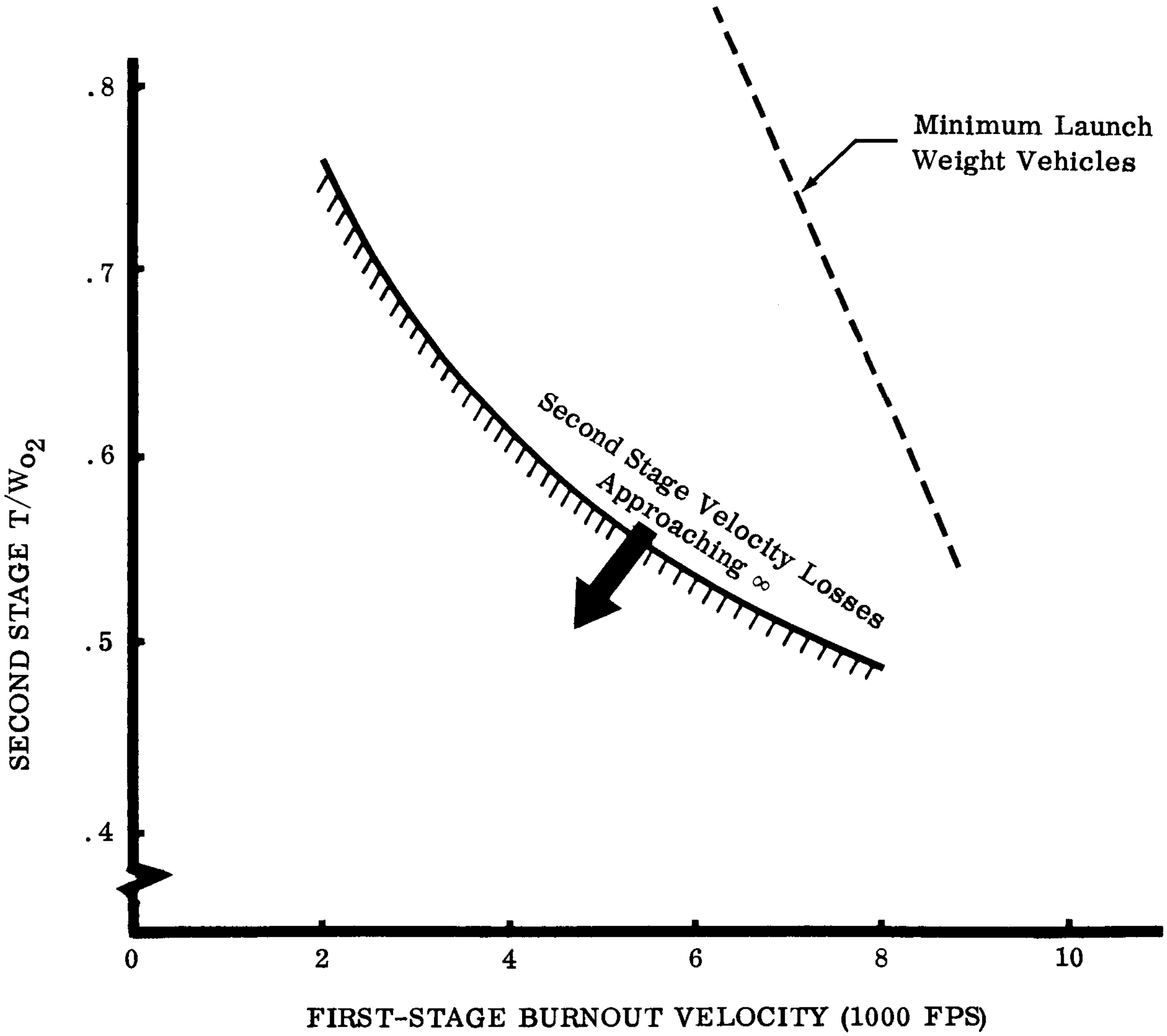


THRUST-TO-WEIGHT RATIO LIMITS

Second Stage

The previous chart has indicated that the velocity losses are less than 3,000 fps for minimum launch weight vehicles. However, it may not always be practical to select vehicles on this basis. The minimum required T_2/W_{O2} in order to keep the velocity losses from not exceeding 10,000 fps are shown.

THRUST-TO-WEIGHT RATIO LIMITS
Second-Stage



MOTOR CROSS-SECTION LOADING

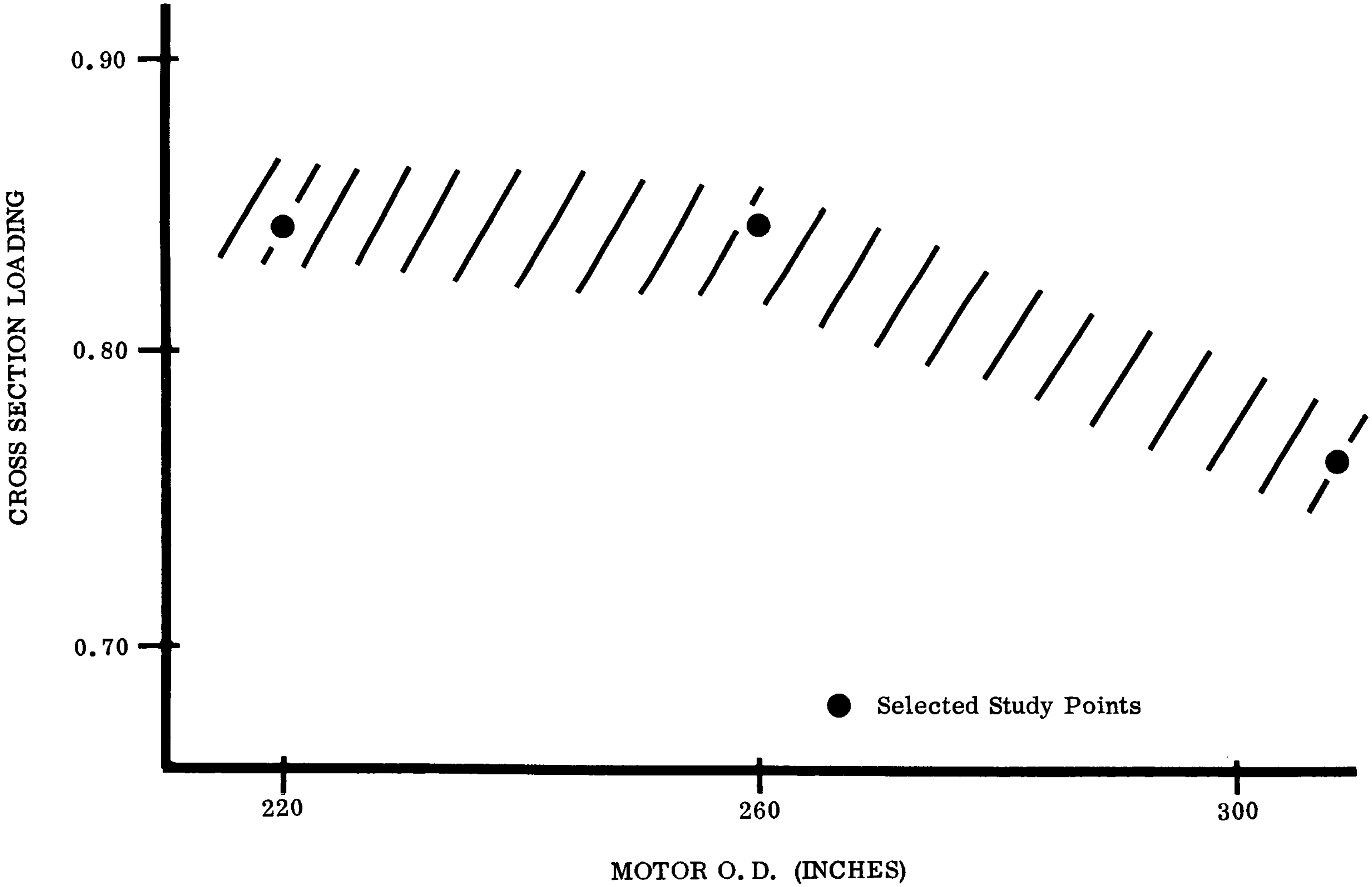
The mass fraction and resulting performance of a large solid-propellant motor is heavily influenced by the volumetric efficiency with which the motor can be loaded with propellant.

In general, main considerations limiting the cross-section loading are: propellant structural properties, burning time and rate, and thrust-time trace. Excessive stresses on the propellant must be avoided by providing adequate internal radii and star-point base areas. The propellant web thickness must be consistent with the propellant burning rate capability, the desired operating pressure, and burning time. Also, the grain port configuration must develop the burning surface needed for an acceptable thrust-time history.

Assuming a monolithic internal burning star grain configuration, current moderate-performance propellants, and a reasonably constant thrust-time requirement, a trend is established in the cross-section loading as a function of motor diameter. Specific motor designs are noted.

This trend is basic in the further evaluation of large solid-propellant motors to be undertaken in Task II of the current NASA study.

MOTOR CROSS-SECTION LOADING



MOTOR CHARACTERISTICS STUDY PLAN

Typical large solid-propellant motor performance data to be developed during Task II for the 260-inch motor is shown in the chart.

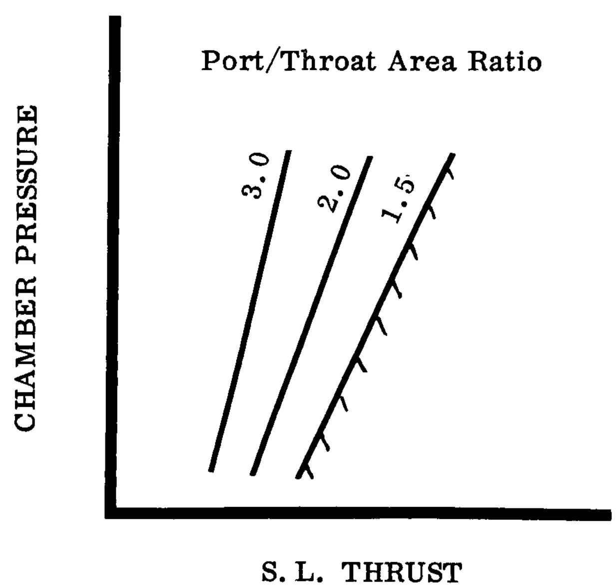
Assuming a cross-section loading in the trend shown in previous charts and a propellant similar to that used in the first stages of current large solid vehicles, chamber pressure and propellant weight are plotted as functions of sea level thrust. Several constraints are indicated.

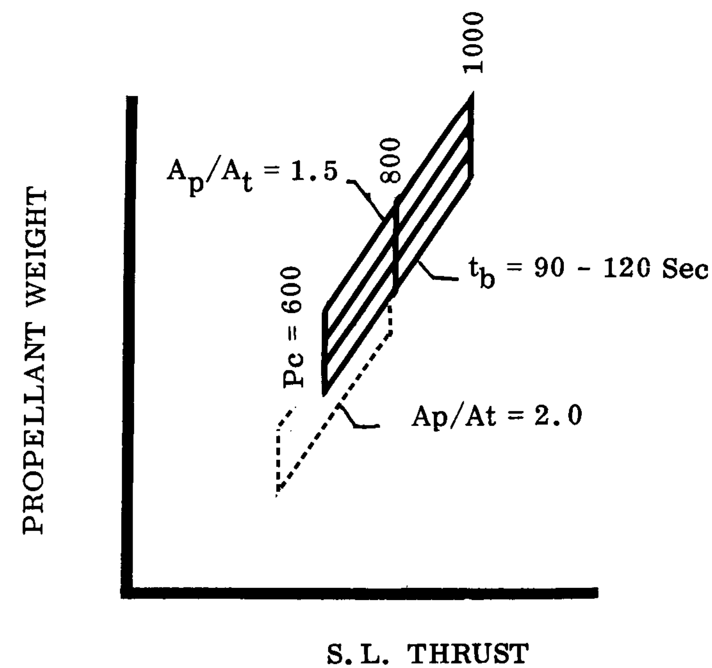
A near-maximum sea level thrust obtainable from the 260-inch motor, as a function of chamber pressure, is shown in the left hand plot at a port-to-throat ratio of 1.5. The effect of higher port-to-throat ratios reflecting either higher chamber pressure or lower thrust requirement is shown. Propellant grain configuration is constant across both plots. Motor performance parameters will be calculated in terms of their effective equivalents, and reduced to web and action time value for an assumed grain configuration.

The right hand figure shows motor performance envelopes at port-to-throat area ratios of 1.5 and 2.0. A web fraction of 0.44 is assumed. A burning time limitation will fall diagonally upward across the envelopes, making only the longer burning times available for this motor. The exact limit will be fixed by the specific propellant formulation assumed.

MOTOR CHARACTERISTICS

Study Plan





STUDY PLAN

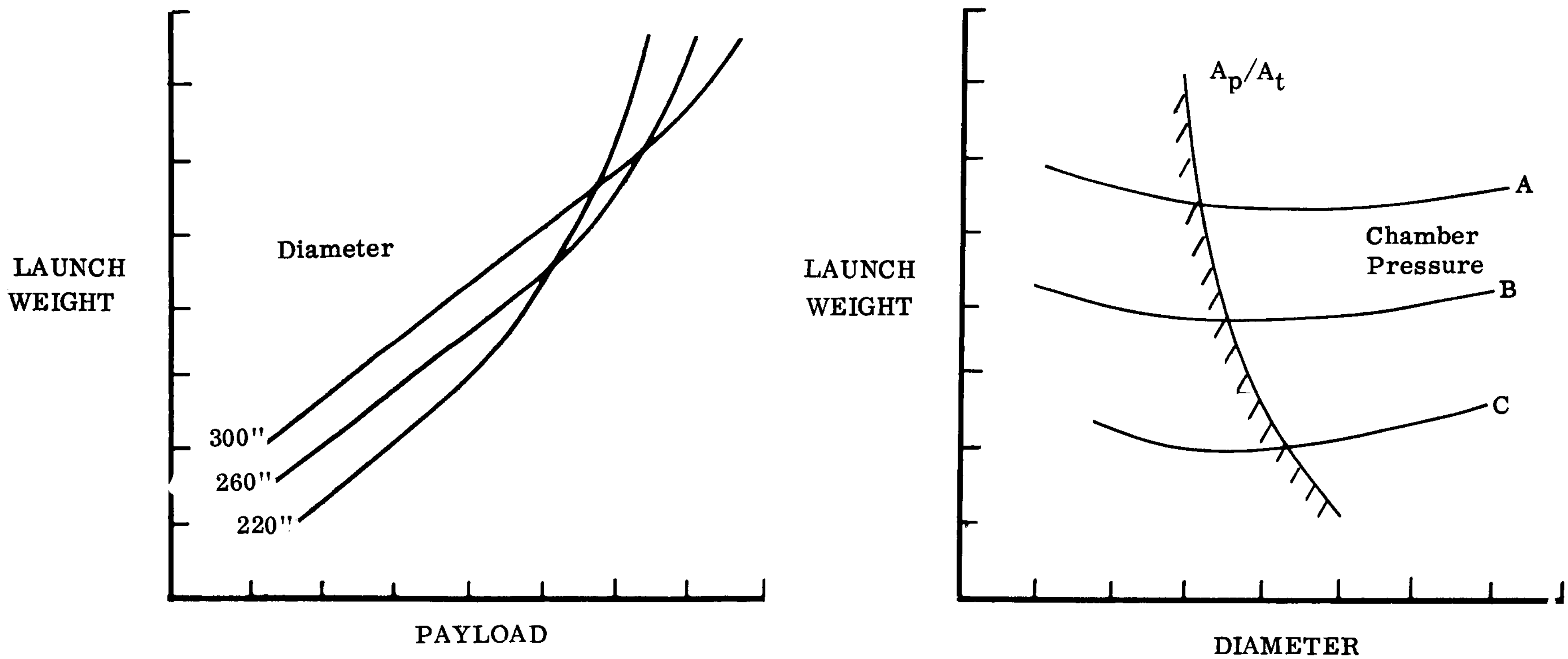
Study results presented in previous charts are for the first phase of Task No. 2 and are preliminary. Final results will include revisions of the basic input data (inert weight and propulsion characteristics).

An outline of the study plan is presented in the chart. This plan covers the essential elements mutually adopted for the NASA Solid Nova, Task No. 2 studies.

[redacted]

STUDY PLAN

Parametric Study



- Second-Stage Motor Study
- Escape Payload Study
- Engine-Out Study
- Alternate Mission
- Trade Factors
- Selected Vehicles

[redacted]

STATUS SUMMARY

1) Structural dynamic and static analyses are nearly complete. The resultant data will provide the tools necessary to proceed with detail structural design.

2) The cluster structure concept recommended for further development incorporates a skirt-type base support using three support points per motor and a one-end-fixity cluster structure using the cross-beam configuration.

3) Initial control system requirement studies indicate major influence by the wind profile used. Final requirements when established may have major effect on TVC system choice.

4) TVC system analysis has determined that two systems should be given further detail consideration — the 4000-psi closed-loop gimbaled-nozzle system and the N_2O_4 fluid-injection system. It is planned that one of these will be incorporated in the vehicle preliminary designs.

5) Solid-motor optimization studies are essentially complete. Determination of most desirable thrust tail-off characteristics for ease in staging remains. These characteristics will become fixed when staging studies, now in process, are completed.

REMAINING TASKS TO BE PERFORMED

1) Complete the structural and dynamic control analysis. Reduce to forms applicable for evaluation and design use.

2) Review TVC system evaluation taking into account the findings of the dynamic control analysis. Reduce evaluation techniques to forms applicable to future evaluation and design.

3) Initiate and complete final vehicle preliminary designs incorporating the chosen clustering structure concept and TVC system. Resize the vehicle as required to produce a maximum payload-to-weight ratio when the optimum structural, subsystem, and propulsion system inputs are incorporated. Results are to be in the form of preliminary design specifications.

4) Complete an engine-out trajectory analysis as required to estimate TVC system requirements to maintain control, and for range safety considerations.

5) Complete the vehicle reliability studies and estimate a development test vehicle requirement.

6) Estimate total system costs and formulate development and funding plans.

7) Make recommendations for follow-on work. This will include experimental testing to confirm analytical techniques.

8) Initiate and complete final report documentation.

BLANK